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EFFECT OF A SEA-LEVEL CANAL ON THE GROUND-WATER LEVEL OF FLORIDA.

SIDNEY PAIGE.

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ACKNOWLEDGMENT.

THE Corps of Engineers, U. S. Army, has for the past five years carried on intensive and extensive field and office investigations designed to select the best route for an Atlantic-Gulf Ship Canal across Florida. The paper that follows is based on results of this work, supplemented by the extensive and valuable work carried

on by the U. S. Geological Survey and the Florida Geological Survey.

I wish to acknowledge the unremitting cooperation of Clarence E. Boesch, Head Engineer, E. B. Burwell, Geologist (familiar for years with the problem), Frank C. Carey, Principal Engineer, and Malcolm Pirnie, Consulting Engineer of New York (engaged for years in problems connected with water supply in Florida).

GENERAL.

A sea-level canal will change in a limited area the shape and volume of the underground water reservoir of the Florida peninsula.

In order to predict the magnitude of these changes, and therein the effect of the canal on the underground water supply of the State, it is necessary to understand and weigh the elements that control the present shape and volume of the entire reservoir, and to determine wherein and to what degree the digging of the canal will tend to alter these elements. An answer should lie in correlating the physical features of the terrain—topographic and geologic (and the history of development of those features) with the mechanics of ground-water charge and discharge.

In the review that follows detail is introduced only where relevant to the main issue, the charge, storage, and discharge of ground-water, and the effects produced on the reservoir by the cutting of the canal.

TOPOGRAPHY AND DRAINAGE.

The peninsula of Florida is a low plateau about 375 miles long and 140 miles wide not exceeding in any place an elevation of 330 feet. The State is but the land portion of a much larger submerged peninsula, a part of the continental shelf that protrudes southeastward from the borders of the continent. (Fig. 1.) On the east the continental shelf is abruptly terminated by an escarpment, near the coast at the southern end of the State but progres-

sively offshore toward the north. To the west the bordering escarpment, at the edge of the shelf, is far offshore.

Much of the surface of Florida lies below the 50-foot contour; all of the State in fact, south of Lake Okeechobee. North of this lake, in general, the high ground is contiguous to the 82d meridian, though there are exceptions to this statement. (Fig. 2.)

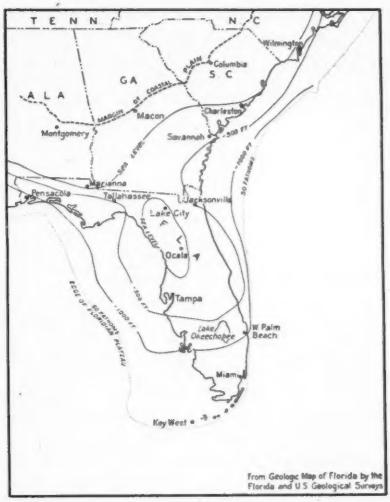


FIG. 1. Sketch Map of Florida and Adjacent States Showing Structure by Contour Lines on Top of the Eocene formations. Datum is Mean Sea Level.

Much of the stream drainage of the peninsula is controlled by (1) a topographic "high," south of the canal, and east of Lakeland in Polk County, from which streams flow northward, westward, and southward, and (2) a topographic "high," north of the canal, in Putnam County, from which streams flow north, east, south, and west. Between these two "highs" there is generally lower ground along the course of the canal-route, wherein lies a drainage divide located near Ocala, separating the waters of the

ATLANTIC
OCEAN
GULF OF MEXICO
N
ATLANTIC-GULF SHIP. CANAL
100 CONTOURS AT INTERVALS OF 50 FT
SCALE IN MILES
0 5 10 20 30
GENERALIZED TOPOGRAPHIC MAP OF FLORIDA PENINSULA

FIG. 2.

Oklawaha from those of the Withlacoochee River systems, the former draining to the Atlantic, the latter to the Gulf.

The drainage of the extreme eastern part of the peninsula along its entire length is not related apparently to the "highs" mentioned above. Two river systems drain this narrow strip, one the St. Johns system flowing northward for roughly 140 miles and reaching the sea near Jacksonville, the other the Lake Kissimmee system draining southward to Lake Okeechobee. The heads of these systems overlap on a very low water divide. Both streams roughly parallel the sea, flowing along coastal terraces, the surfaces of which have probably not been greatly modified since their emergence from beneath the sea.

There are countless lakes and swamps over much of Florida and many large springs, and over immense areas there has been developed a remarkable sink-hole topography. The significance of these features will be emphasized later.

In summary, it is apparent that the peninsula of Florida is a nearly flat, very low-standing, wet plateau having a 52-inch rainfall, more or less, equal to 900 million gallons per square mile, and fashioned to absorb much water.

STRATIGRAPHY.

The peninsula of Florida is underlain by a series of sedimentary beds roughly 4,000 feet in thickness, that range in age from Cretaceous to recent. The assemblage rests on a basement of crystalline rocks. Only beds of Eocene or later age are exposed at the surface or will be cut by the canal.

From the standpoint of water storage the formations exposed, and for a considerable depth below the surface, are susceptible to an important distinction and subdivision. There is (1) a lower series, of marked though not perfect homogeneity, comprising rocks of Eocene and Miocene ages, largely limestone—the Ocala and Tampa limestones (and Eocene limestones beneath them); (2) an upper series of Miocene, Pliocene, and Quaternary age, comprising at the base the sandy limestones, clays, and shell marls of the Hawthorn formation (Miocene) and the sands, clays,

marls, lying above the Hawthorn (Pliocene and Quaternary).

The Hawthorn formation lies unconformably on the Eocene beds (Ocala limestone) and in parts of the State to the north Oligocene beds are present between the two, but these latter formations hardly concern us for they are not present near the canal and serve (by their absence), only to point explicitly to the unconformity. The Hawthorn beds are believed to be conformable with the Tampa limestone (Miocene) which overlies the Ocala limestone.

The distinction between the lower series, largely limestones, and the upper series, heterogeneous sandy limestones, clays and sands and marls, is of the first importance in any consideration of ground-water storage and discharge in the Florida peninsula, and the difference will be repeatedly referred to in the discussion of charge and discharge of reservoirs that follows.

STRUCTURE.

The beds underlying the peninsula of Florida were laid down essentially horizontally, or with very low initial dips. Today these rocks, including their submerged extensions on the continental shelf, have the form of a very gently warped elliptical dome with a longer axis extending roughly north-northwest, and with its crest a few miles northwest of Ocala. The progress of uplift of this dome extended over a long period and the details of the shape of its warped surface played an important part in controlling erosion of the surface beds, and thus indirectly affected the charge and discharge of underground water and the position of areas of artesian storage.

The dome began to rise at the close of Eocene time. During later Miocene stages it was submerged, and the sandy limestones of the Hawthorn formation were deposited. Since Miocene time uplift has continued and considerable portions of this once continuous cover of Hawthorn have been eroded away.

PHYSIOGRAPHY.

The development of land-forms on the peninsula was closely related to the progressive uplift of the terrain, to the distinction

between the character of the beds of the upper and lower series, and to the domical shape of the uplift. Pleistocene marine terraces originally developed on the two sides of the peninsula were related perhaps to meltings of the Polar icecaps. These terraces are beautifully displayed on the eastern side, but have been partly or wholly destroyed by later erosion on much of the western side of the peninsula. The asymmetrical shape of the dome, with steeper dips above sea level on the western side, resulted in steeper stream gradients to the west and consequently more rapid erosion; the upper series was here stripped off more rapidly than on the east side and the underlying Tampa and Ocala limestones earlier exposed to erosion. And these, once exposed, and being more susceptible to erosion than the overlying upper series, were planed down in a regular degradational slope extending from the water divide to the sea. There remained an elliptical area, occupying the northwestern side of the peninsula, wherein the Ocala and Tampa limestones are exposed at the surface (Fig. 3), an area having an important relation to the intake and discharge of underground water.

Wherever the Ocala or Tampa limestones are exposed at the surface today and this surface stands above the water table, or has in the past stood for long periods above the water table, or where this surface is overlain by permeable cover of the Hawthorn formation, the limestone surface is pitted with innumerable conical or subconical depressions that extend downward to points of lateral flow of the descending water. These openings in that portion of the dome above sea level vary from a few inches in diameter and a few inches in depth, to large sinks many feet across and descending to the present ground water surface or to the position of a former, lower water table. The diameters of these openings are not always a measure of their depth. Some broad openings are shallow, whereas a narrow opening nearby may descend many feet to or below the water table, or vice versa. In the normal course of events sands and clays of the overlying formations collapse into these openings. It is apparent that their depths are related in part to the supply of carbon dioxide or vegetable sol-

vents in the descending rainwater. It is also apparent that their depths are limited by the development in the adjacent rock of capacity for lateral flow sufficient to carry off the descending rainwater. The porosity of the formation as affected by them must in consequence diminish as depth is attained. Connecting

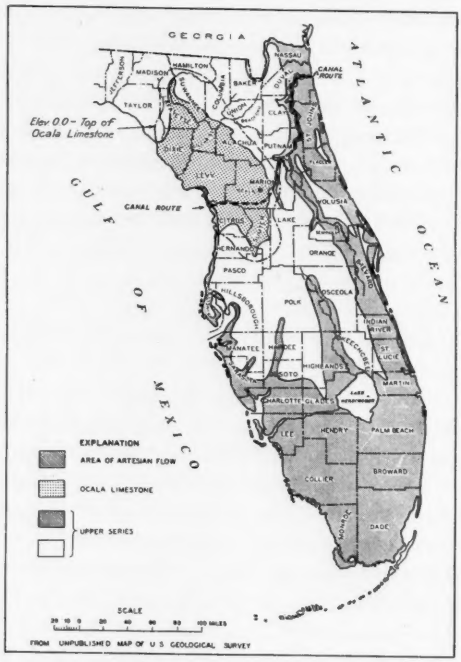


FIG. 3. Map of Florida Showing Area of Artesian Flow and General Areal Geology.

these cavities in many places, there exist ramifying systems of tortuous channels, large and small, that facilitate the lateral movement of ground water in the limestone, and have much to do with setting up subterranean drainage systems.

Movement of water within the uppermost portion of the lime-

stone is decidedly free, and it is largely due to this fact that the water table is so flat over much of the terrain underlain by the Ocala limestone. It is to the presence of these solution cavities that the sink-hole topography of such extensive areas is due. Along the ground water-table slopes, away from the established highs in many of these sink holes, now clogged with sand and clay carried down into them from the overlying formation, lakes have accumulated that are perched above the general water table. Many of the lakes of Florida have been formed in this way, notably near the southern ground water high area called " the lake region," though many others represent simply depressions in the surface of the ground below the piezometric level. Some lakes at the summit of the southern ground-water high are included in the latter class.

One may conclude that the process described above is largely a superficial phenomenon and that the resistance to underground flowage through the limestone is certainly greater at greater depths. This aspect of the problem will be referred to again, and the development of drainage channels beneath the water table will also be discussed.

GROUND-WATER CHARGE AND DISCHARGE.

Reservoirs.—A certain amount of rainwater falling on the surface of dry porous rock will be absorbed and move downward. On encountering impermeable strata such percolating water will form a body of water in the voids of the porous rock immediately above the impermeable stratum, and tend to spread and assume a flat surface. The final curvature of the surface (Fig. 4) of such a body of water will be determined by (1) the rate at which the water is supplied from above; (2) the resistance offered by the rock to the lateral flow of the water through it to some outlet. With a fixed rate of lateral flow the curvature of the water surface will vary with the rate of rainfall. With a fixed rainfall rate the curvature will vary with the rate of lateral flow of water through the rocks. The system is at all times one of continuous circulation maintained in balance only by virtue of continued rainfall

at a rate sufficient to compensate for all losses due to lateral flow. If the rainfall is sufficient to raise the surface of the ground-water to the surface of the land at any place, then a surface run-off will

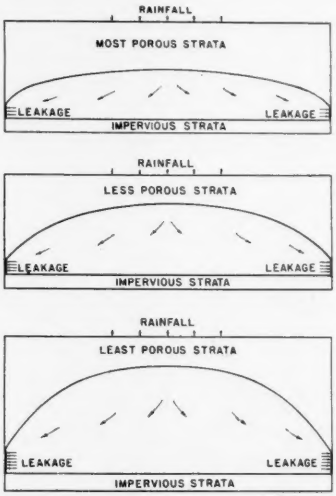


FIG. 4. Diagrammatic Illustrations of the Formation of Reservoirs in Rocks of Different Porosity Based on Equal Rainfall.

be initiated (streams and springs), or standing bodies of water will be formed (lakes and ponds and swamps) (Fig. 5).

It is important to recognize that the volume of water in the type of reservoir illustrated in Fig. 4, is strictly limited to that held

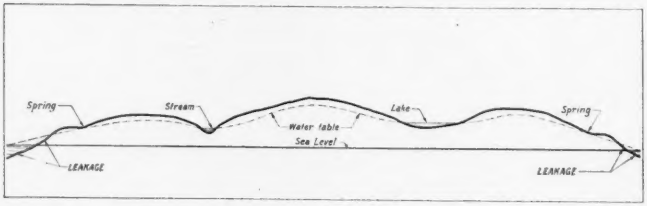


FIG. 5. General Relation of Ground Water to Topography.

between the impermeable stratum at the base and the water table. No storage is developed below the surface of the impermeable stratum.

If now there be substituted for the above system dependent on an impermeable stratum a system based on downward percolation into a mass of porous rock saturated up to sea level with salt water, a very different type of storage reservoir is set up. Rain water now absorbed by the porous rock and moving downward will on reaching the salt water at sea level depress the surface of the latter by displacement of salt water. The weight of the salt water displaced below sea level will always, when flow to reach balance has ceased, equal the weight of the mass of fresh water floated on it. Thus a column of fresh water will stand above sea level and be underlain by a much deeper column of fresh water below sea level. (The ratio of the two depending on the ratio of the specific gravities of fresh to salt water. For every foot of fresh water above sea level there will be about 38 feet of fresh water below sea level) (Fig. 6–*A*).

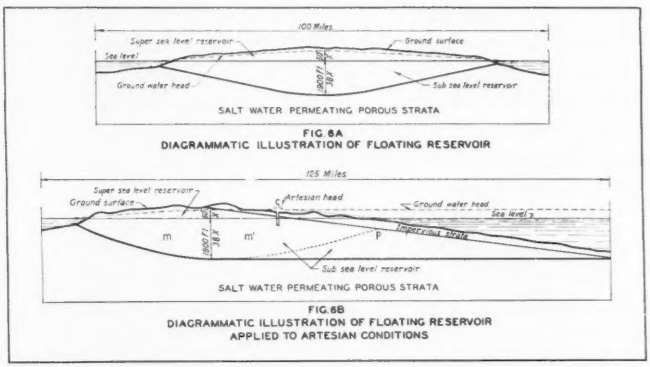


FIG. 6A
DIAGRAMMATIC ILLUSTRATION OF FLOATING RESERVOIR

FIG. 6B
DIAGRAMMATIC ILLUSTRATION OF FLOATING RESERVOIR APPLIED TO ARTESIAN CONDITIONS

So long as the weight of fresh water can be increased by a supply of water from above, just so long will the salt water be displaced downward to greater depths. The limits of this depth are controlled by the principles of the circulation described above,

and in any case the depth is limited by the height of land above the reservoir. Provided there is unlimited height of land above the reservoir the system is always controlled by the ratio between the rate of lateral flow of ground-water through the rocks (to points of escape on the surface or into the sea) and the rate of rainfall controlling the supply from above. Sooner or later the increased head developed above sea level will increase the wasting through the rocks, or at the surface (streams, springs, lakes, evaporation), and thus bring about a balance.

The characteristics of this floating reservoir may be compared to those of a floating block of ice. The mass of such ice above water level is supported by the excess weight of water displaced below water level. If some ice is removed from the top of the block the entire block rises an amount governed by the difference in specific gravities of the ice and water—that is, the removal of the ice at the top disturbs the balance of the system. In the case of the floating reservoir similar forces are potentially operative, but the effect is delayed by frictional resistance to vertical flow of the water through the rock. Nevertheless the removal of water from the top of the reservoir decreases the weight of the floating mass of fresh water so that the salt water rises as rapidly as it can force the fresh water upward against the resistance of the rock to vertical flow, until balance is reached. Inasmuch as the specific gravity of salt water is only slightly more than fresh water, the volume of fresh water that may theoretically be stored underground is enormous.

The above discussion applies to a floating fresh water reservoir, open at the top, in porous rock, and underlain and surrounded by salt water below sea level. Under the conditions illustrated in Fig. 6–*B*, however, a floating reservoir system will set up artesian head.

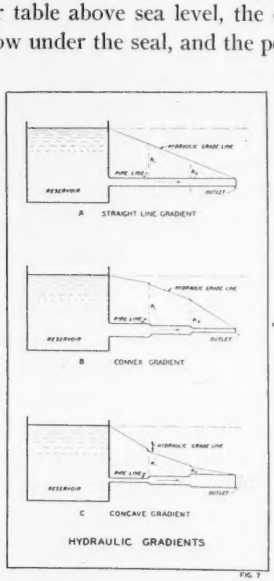
Here the land mass is bordered by the sea. Near the center of the land mass impervious beds are shown dipping to the right, overlying homogeneous porous strata. The fresh water columns x underlain by the fresh water columns 38x are floating on depressed sea water. Fresh water will be forced down beneath the

impervious strata until it has depressed salt water to the uniform depth of 38x. A well drilled at c will develop artesian head. The area of potential artesian head extends out to sea. This condition in places is closely approximated in Florida today.

If the depth below sea level at which the pervious beds in an artesian system outcrop is equal to or greater than the depth of salt water column necessary to balance the fresh water head above sea level under which water is supplied to the pervious beds, then leakage to the sea through these beds is stagnated. Under such conditions the system would be thrown out of balance until one of the following conditions is met: (1) The fresh water head must build up sufficiently high to discharge the required amount of water through the porous beds to the sea; (2) the surplus water must be discharged on land through springs and seepage; (3) the water must travel along the coastal belt until higher points of escape are found where the salt water column will permit escape. Such conditions prevail along the Florida coast from Tampa to Palm Beach, for here the Ocala limestone outcrops on the continental shelf at such great depths that the existing fresh water heads in the hinterland are insufficient to produce flow to the sea. As a result, the surplus water that does not escape at the surface is forced to travel in northeasterly and northwesterly directions to escape along the Gulf coast north of Tampa, and along the Atlantic coast north of Palm Beach where the Ocala outcrops on the shelf at higher elevations. This condition prevails, as is shown by the fact that ground-water on the eastern and western flanks of the southern water-table high is highly mineralized. Much of the high mineral content must have come from other sources than the reservoir rocks through which it percolates in traveling from the high to the flanks. It is believed to be due to a considerable extent to contamination from the highly mineralized waters of southern Florida moving northeastward and northwestward to escape.

Where leakage develops through the overlying strata the position of the point P is moved to the left and the bottom of the reservoir becomes a curved surface. This condition also exists

today off the eastern and western coasts of Florida. The relative position of the point P depends on a number of variables—the depth of fresh water, H, the dip of the impervious strata, the height of the water table above sea level, the development of capacity for lateral flow under the seal, and the perfection of sealing



HYDRAULIC GRADIENTS

FIG. 7

by the relatively impervious beds. In the last analysis a balance will be set up between the total intake and the total losses of the system.

In summary, the important characteristics of the floating reservoir system are as follows:

(1) The system is never static, but is always a circulating system with total intake balanced against total losses. The volume of the reservoir is always fluctuating.

(2) The depth of fresh water storage below the level of the sea is approximately 38 times the height of fresh water above sea level.

(3) To lower the water table permanently 1 foot, it is necessary to withdraw 38 feet of water from sub-sea-level storage.

(4) The permanent lowering of the water table 1 foot implies a rise of 38 feet in the level of the underlying salt water surface.

Hydraulic Gradients.—It should be clear from the above that in a terrain of diverse topography and beneath which there are rocks of varying porosity (or capacity to carry lateral flow of water), the upper surface of a floating reservoir will be irregular. There will be water-table "highs" and "lows." The slopes of the surface of these "highs" may be termed the "hydraulic gradients" of the water table. Now, theoretically in such a system of pipes as is illustrated in Fig. 7*a*, the hydraulic gradient is a straight line, the slope of which is dependent on the ratio between the hydraulic "head" of the system and the resistance to flow within the system. But here it is important to note that the system illustrated is supplied with water at one point on the pipe only—at the intake end. But the reservoir system under discussion, in which water moves through a roughly homogeneous mass of rock which may be considered as made up of an infinite number of interconnecting pipes, is supplied with water all along the line of the gradient, that is, there is a multitude of intake areas and but a limited number of outlets. Hydraulic gradients therefore should approximate convex curves with increasingly steep gradients toward the points of outlet, as indicated in Fig. 7*b* unless passages of large capacity are developed near these outlets, in which case they become concave, as indicated in Fig. 7*c*. Where the topography of the terrain is such that the surface of the underground reservoir (the water table) is intersected by the surface of the land (preventing intake of water) a break occurs in the hydraulic gradient. From such a point forward toward lower outlets, a new gradient is set up.

THE UNDERGROUND RESERVOIR OF FLORIDA.

Nature, Shape, and Volume of the Reservoir.—The greater part of the State of Florida is underlain by an immense body of fresh water. Bordering certain portions of the coast on both sides of the peninsula this water, where confined beneath relatively

impervious strata, extends off-shore as an artesian reservoir beneath the bottom of the sea.

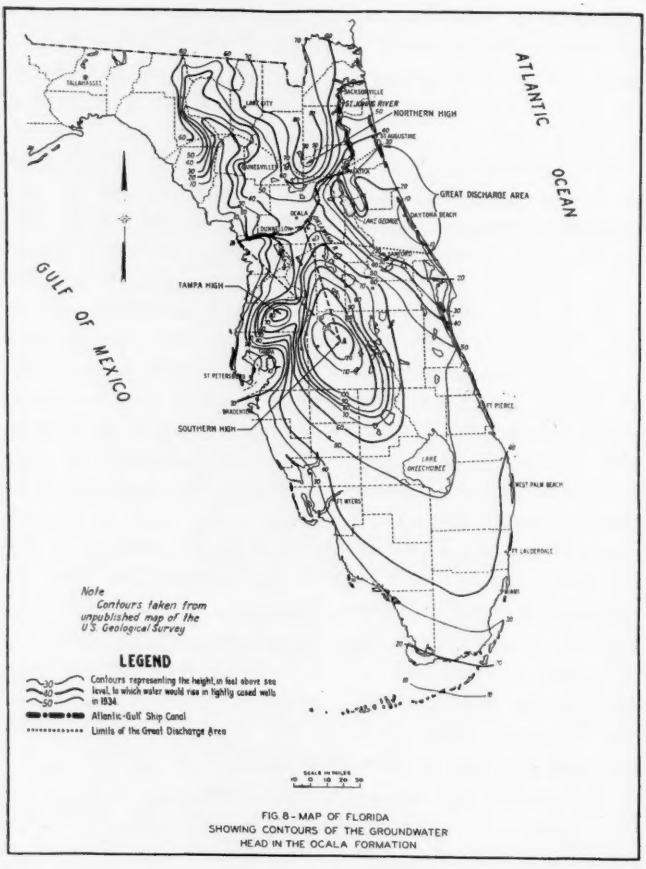

ATLANTIC OCEAN
GULF OF MEXICO
NORTHERN HIGH
GREAT DISCHARGE AREA
TAMPA HIGH
SOUTHERN HIGH
Note
Contours taken from unpublished map of the U.S. Geological Survey
LEGEND
Contours representing the height, in feet above sea level, to which water would rise in tightly cased wells in 1934.
Atlantic-Gulf Ship Canal
Limits of the Great Discharge Area

FIG. 8 - MAP OF FLORIDA
SHOWING CONTOURS OF THE GROUNDWATER
HEAD IN THE OCALA FORMATION

This body of fresh water should be regarded as a single great reservoir, the accumulation, movement, and discharge of which is governed by the laws underlying the movement of water through

rocks under the influence of gravity, and particularly by the laws governing an underground reservoir floating on sea water, as set forth above.

It is important to recognize that the rocks containing the underground reservoir fall into two divisions, an upper series which, while it will absorb water, yields it with relative difficulty; and a lower series that absorbs water and yields water relatively freely, because channels have been developed within in. It appears unmistakable now that the water contained in the two series acts as a unit, constituting a single great reservoir.

A critical examination of the shape of the upper surface of the reservoir and a correlation of its significant features with the geology of the underlying formations should throw light on the principles governing the operation of the reservoir.

Fig. 8 shows contours (10-foot intervals based on sea level) on the piezometric surface of water in the Ocala limestone. Over part of the area the Ocala limestone is exposed at the surface. (Fig. 3.) Here the contours indicate the elevation of the water table in the Ocala limestone. Over the remainder of the area the Ocala limestone lies beneath the upper series, a cover of variable thickness. Here the contours indicate the elevation to which Ocala water will rise in a tightly cased well. In many places this elevation lies beneath the surface of the ground. At other places this elevation is above the surface of the ground, *i.e.*, artesian conditions are set up (Fig. 3).

The beds of the upper series overlying the Ocala limestone also contain water but more tenaciously held. It is nevertheless true that this water exerts pressure on the water in the Ocala beneath, and together with it forms a single great reservoir. The only difference between ground-water in the upper series and in the Ocala limestone is in its rate of flow. The upper series holds its water tenaciously while the Ocala limestone gives it up much more freely.

Three major piezometric "highs" are displayed on Fig. 8. The first is located in Clay and Putnam Counties, north of the canal. Here the piezometric surface rises above 90 feet. The top

of the Ocala limestone beneath this "high" is 100 feet below sea level. The surface of the ground is not less than 160 feet above sea level. Thus there is present not less than 260 feet of the upper series, of which about 190 feet at least is saturated with water. There is no known cause of pressure capable of raising the Ocala water in wells to 90 feet above sea level at this "high," other than the weight of the entire water column at this place. One is forced to the conclusion that the water in the upper series is pressing on the Ocala water, that is, the water column is acting as a unit. The relation of the ground-water body to the upper and lower series and to the topography of the terrain is illustrated in Fig. 9 (*A* to *D*).

South of the canal, in Polk County, there is a second water-table "high." Here, in wells drilled into the Ocala limestone, water will rise to 135 feet above sea level, with the surface of the ground approximately 175 feet above sea level. The top of the Ocala limestone lies 100 feet below sea level. From this "high" the piezometric surface slopes downward in all directions. There is no known cause of this piezometric "high" in Ocala water, other than the overlying column of water saturating the rock of the upper series. Here, also, one is forced to conclude that the body of ground-water acts as a unit. Toward the east two areas of artesian head are developed, separated by a zone of nonartesian flow (Fig. 3). The first area lies in the depression of the Lake Kissimmee River system. The second underlies the low coastal plain bordering the sea and passes out to sea.

The third "high" lies in Pasco County above Tampa Bay. Here Tampa limestone is exposed at sea level, rising inland to elevation 90, and is underlain immediately by Ocala limestone. The piezometric surface takes the form of a relatively steep dome, its summit something over 90 feet above sea level. There can be no question here but that we are dealing with a saturation zone embracing both Ocala and Tampa limestone; that the pressure is symmetrically distributed through both formations, and that the "head" is caused only by the weight of the column of water in the immediate vicinity.

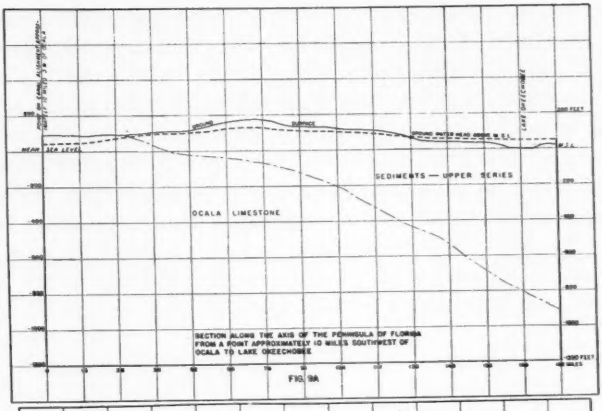

SEDIMENTS — UPPER SERIES
OCALA LIMESTONE
SECTION ALONG THE AXIS OF THE PENINSULA OF FLORIDA FROM A POINT APPROXIMATELY 10 MILES SOUTHWEST OF OCALA TO LAKE OKEECHOBEE

FIG. 9A

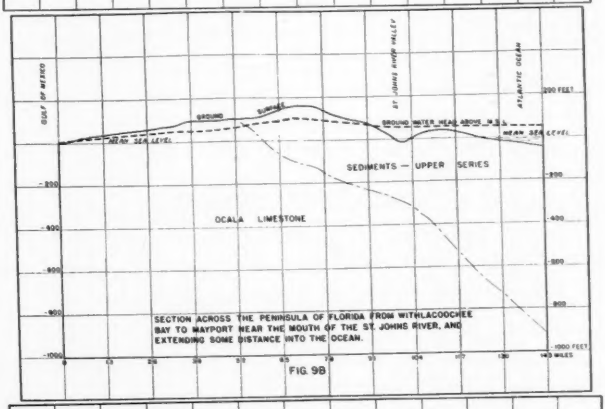

GULF OF MEXICO
ST. JOHNS RIVER VALLEY
ATLANTIC OCEAN
SEDIMENTS — UPPER SERIES
OCALA LIMESTONE
SECTION ACROSS THE PENINSULA OF FLORIDA FROM WITHLACOOCHEE BAY TO MAYPORT NEAR THE MOUTH OF THE ST. JOHNS RIVER, AND EXTENDING SOME DISTANCE INTO THE OCEAN.

FIG. 9B

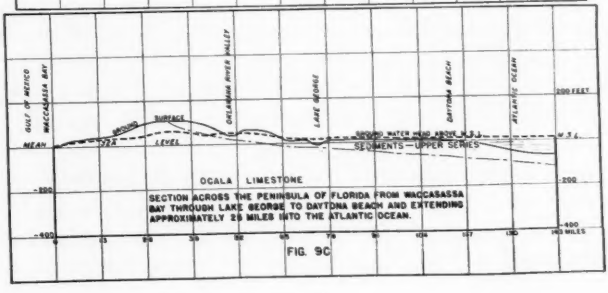

GULF OF MEXICO
WACCASASSA BAY
OKLAWAHA RIVER VALLEY
LAKE GEORGE
DAYTONA BEACH
ATLANTIC OCEAN
SEDIMENTS — UPPER SERIES
OCALA LIMESTONE
SECTION ACROSS THE PENINSULA OF FLORIDA FROM WACCASASSA BAY THROUGH LAKE GEORGE TO DAYTONA BEACH AND EXTENDING APPROXIMATELY 25 MILES INTO THE ATLANTIC OCEAN.

FIG. 9C

It may be questioned why, if we are dealing only with a single water column, permeating porous rock, artesian conditions are developed under parts of the terrain.

The answer lies in the fact that water moves far more slowly and is retained far more tenaciously in the upper series than in the lower series; that depth of cover (progressively effecting a better seal), plays the principal part in the mechanism of the process; and that the artesian conditions arise for the most part, in very

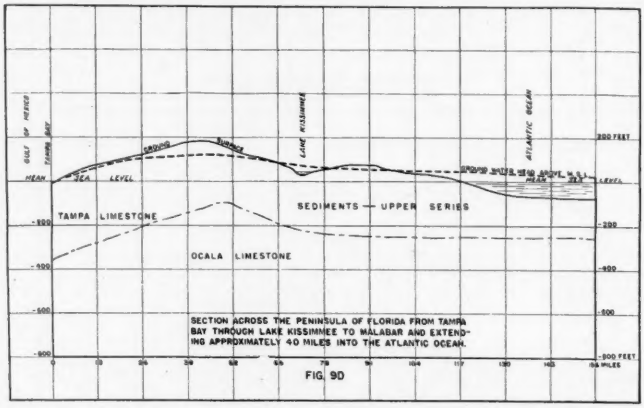


FIG. 9D

low standing water-soaked territory, or beneath the sea under sufficient cover; that over much of this latter territory, leakage from below is slowly taking place, through the upper series, notwithstanding artesian conditions. Note for example the artesian zones along the drainage channels of the Peace Creek and Kissimmee River systems draining south from the southern "high" (Fig. 3) also the drainage channel of Oklawaha River and that bordering the entire course of St. Johns River, particularly the region around Lake George, obviously a leaky zone.

There is other evidence to show that the underground water reservoir as a whole is a single unit; for example, neither the southern nor northern "high" is located on the high point of the structural dome of the peninsula. The northern "high" lies on

the northeast flank of the dome, a position controlled more by topography and the character of the underlying formations than by structure of the Ocala limestone; the southern "high," taken as a whole, although in part on the long axis of the fold, trends north to the east of the axis, and lies to the south of the high point of the dome.

For every protuberance of the water reservoir as a whole, above sea level, there must be envisaged a projection of the reservoir downward beneath sea level approximately 38 times as great. Where a thick cover of the upper series overlies the Ocala limestone, artesian conditions have driven a portion of the reservoir beneath the sea.

Subterranean Drainage. — Water percolating downward through a porous rock under the force of gravity finally reaches the water table. In Florida, measurements indicate that between a third and a half of the rainfall on surfaces lying above the water table in the open reservoir enters the reservoir, the remainder being lost in evaporation or transpiration of plants. In a reservoir of the "floating" type it can be shown that under each groundwater summit ("high") the pressure to create lateral flow is equal at all depths, from sea level to the bottom of the fresh water reservoir. Accordingly, lateral flow is taking place through the porous rock at all fresh water depths, a movement toward ultimate discharge on the land or near sea level in the "open reservoir" or at depths below sea level under appropriate artesian conditions; the movement being naturally more rapid in the more porous strata than in strata of denser rocks. The continuous supply of rain-water reaching the top of the underground reservoir has capacity to dissolve substantial amounts of limestone and its greatest solvent action is exerted in the upper parts of the limestone mass. The water continuing downward must be a weaker solvent, having taken up a considerable amount of lime.

Thus, inevitably lateral underdrainage systems are initiated at various depths, all of which seek the nearest point of outlet, either on land in intermediate depressions, or near or below sea level

through the rocks. The development and enlargement of a subterranean passage is a slow process extending over a long period of time. At the inception of the process, the flow along the surface of the water table or through the rock beneath the water table is slow and the volume small even in the case of a rock of considerable porosity, such as Ocala limestone, for observation has proved that water does not move very rapidly through Ocala limestone where solution passages are absent.

With time the capacity of the channel is increased by solution, and the capacity of such a channel is greatest at the point of exit, growing progressively less towards the source and dying out in a ramifying system of tributary rivulets.

If it were not for the development of these various lateral underdrainage systems in the porous limestone rock, with capacities sufficient to carry off water laterally at rates many times in excess of the rate of downward flow through the intake blanket, the reservoir of the Florida Peninsula would be filled with water to the surface of the ground, and floods following each heavy rain would establish surface streams cut deeply into all topographical valleys. This must be so since the area of intake is vastly larger than the cross section of the area of outlet. (See discussion below.)

As a matter of observation, immense areas of Florida are without surface drainage. It follows that subsurface drainage is well developed. Attention has already been directed to the porosity or to the development of cavities and solution passages within that portion of the Ocala limestone that stands today or has stood in the past for long intervals above the level of the water table. This condition greatly favors the formation of subterranean drainage patterns. In general, a subterranean drainage pattern is determined by the form of the underground water table which is in turn the result of land forms and the nature and structures of the underlying rocks. Thus, a subterranean river system may drain the surface of the land as truly as does a system of surface streams. The volume of water transported depends on the extent of the area drained, on rainfall

and on the capacity of the solution passages. The slope of the drainage system is a function of all these factors. In such a subterranean river or drainage system, water enters the streams at the sides, bottom and top under a head determined largely by the height of the surrounding water table above the solution passages.

Under artesian conditions, solution passages may traverse the limestone from the areas of intake to outlets at considerable depths out to sea, or to outlets on land where leakage occurs through the cover. At first such escape may be slow, but inevitably the passages are enlarged. In fact, the entire system of subterranean drainage tends to sink deeper beneath the surface, always approaching the base level of the sea, just as surface streams inevitably lower the land surface to base level, provided continental uplift does not ensue.

The following generalization seems warranted: Subterranean drainage systems are highly developed within the underground reservoir of Florida. Through these systems enormous quantities of water pass to the sea along established lines.

It can be shown that the " intake " area of the reservoir comprises an area that embraces about 44 per cent of the peninsula. In general, the direction of flow within an underground reservoir can be read from a piezometric map of the reservoir. Maximum flow is normal to the pressure contours. Movement of water is from the " highs " to the " lows," slowly down " ridge " lines, more rapidly down side-slopes or drainage channels, and the gradient necessary to move the water is indicated by the relative spacing of the contours. In the light of these generalizations, the surface and underground losses from the system may be discussed.

The Concept of Surplus Capacity. It has been shown that the underground water of Florida is but the storage reservoir in a circulating system involving supply (intake), storage (the reservoir), and discharge (escape of underground water to exits), the height of the reservoir at any stage representing a balance between intake and discharge.

It may be useful to compare this floating reservoir system to that of (1) a stream, (2) a leaky dam, with its pool, and (3) a spillway. Rainfall over the intake area (44 per cent of the peninsula) may be compared to the stream; the floating storage reservoir may be compared to the pool; the dam is actually the resistance offered by the rock to the flow of water through it; seepage through the rocks to exits in all subterranean channels may be compared to losses through the dam; while some surface streams may be compared to the spillway. The average height of the water table is the height of the dam.

The effectiveness of a dam is not impaired until leakage through the structure so draws down the pool that the spillway ceases to function. The ratio of loss by leakage to the total intake of the pool is the determining factor in the effectiveness of the system. If the intake greatly exceeds the losses, these latter can be materially increased without lowering the pool.

Now the volume of the intake minus the volume of the spillway should equal the losses through the dam. The water flowing over the spillway at any time represents the excess over all losses. When water just ceases to flow over the spillway the intake should equal the losses. It follows that the volume of water flowing over the spillway is a measure of the safety factor of the system.

Although care must be exercised in their application to the water reservoir of the Floridian plateau, nevertheless these principles supported by those controlling a floating reservoir will explain all the phenomena of the Florida water system, always provided that the geologic and topographic factors of the system are properly correlated and weighed.

Surface run-off cannot, without important reservations, be regarded simply as water lost to storage. In certain systems, in a sense, this may be true, for much water never could reach storage, the time element intervening. For example, rainfall over certain terrains will run off before there is time for it to sink into the ground, even though the ground were very dry, as in terrains with high stream gradients, and underlain by impervious rocks or strata that absorb water very slowly. On the other hand in cer-

tain systems run-off may be regarded certainly as surplus above storage. This is the case in flat terrains at low elevations underlain by porous rocks that absorb water readily. In such systems streams may be regarded as draining the surface of the groundwater reservoir, that is, as a spillway from the pool of the reservoir, and regarded as controlling the height of the reservoir under the particular topographic conditions prevailing over the terrain. If rainfall diminishes, the stream will diminish in volume until it is dried up but the water table cannot fall materially below the level of the stream bottom until the stream does dry up. If rainfall continues at a constant rate, but leakage through the rocks is augmented through any cause whatsoever, the water table will fall until the stream has been absorbed, provided the leakage is sufficiently great. In this sense streams can be thought of as being drawn upon to retard the rate of the fall of the water table in proportion to their volume.

The actual drainage pattern of the Floridian plateau (that portion under consideration) and the actual shape of the groundwater surface beneath it harmonizes in a high degree with the principles outlined above. South of the canal route there are three important drainage systems running northward two of which represent in part surplus run-off above the water needed to fill the storage reservoir, and north of the canal route there are two such systems running southward.

On the western side of the peninsula the Withlacoochee River system flowing north heads against a topographic and water-table "high" in Polk County. This river drains into the Gulf of Mexico at the western entrance of the canal route. About the center of the peninsula is a second river-lake system, that of the Oklawaha, heading against the same topographic and groundwater "high," finally draining eastward into St. Johns River, and thus to the Atlantic Ocean at the eastern entrance to the proposed canal. The headwaters of this system are characterized by the presence of countless lakes and considerable areas of swamp that in general mark the top of the underground water table. On the east side of the peninsula is the third river system,

that of St. Johns River, draining north for 140 miles or more to the Atlantic Ocean at Jacksonville.

The Withlacoochee system may be regarded as spillway water on the west side of the ground-water reservoir; the Oklawaha system with its swamps and lakes as a spillway near the top of the southern dome of the reservoir, while the St. Johns system on the east drains the eastern side of the reservoir. Here, however, it is important to note that the surface of the ground-water reservoir lies in the upper series along the entire length of the peninsula and that beneath this series, artesian conditions prevail with respect to the Ocala limestone; and that along part of the zone, notably in the Lake George region and out to sea, there is substantial leakage of artesian water to the surface.

North of the canal route there are drainage systems draining southward, analogous to those on the south. First, the Blue Springs system on the west, largely subterranean but nevertheless draining the surface of the water table, corresponding to the Withlacoochee system of the south; second, the Silver Springs and Orange Lake system (in part subterranean) corresponding to the Oklawaha system to the south; and third, all the western tributaries of the St. Johns River below Palatka. All these systems head against a topographic and ground-water "high" in Putnam County.

It is clear that the canal route in crossing the peninsula traverses the most important discharge area of the Floridian plateau roughly paralleling the final directions of flow to outlets.

To lower the water table materially over the area embracing the drainage basin of the river systems enumerated, these systems must first be absorbed and essentially cease to flow. All of these drainage systems, in fact all the drainage systems of the plateau, confirm the fact that the present rainfall is sufficient to hold the ground-water table at its present position (essentially a condition of saturation), to support the surface run-off of the rivers and streams, and to support all sub-sea-level losses as well.

After the canal is excavated, and after the water table has been adjusted to the new outlet afforded by the canal, the rate of flow

off the peninsula will be little greater than it has been in the past. Near the canal, however, there will be a change in the ratio between the amount which now runs off underground and the amount which now runs off on the surface, and the volume of the reservoir as a whole will be diminished a certain amount.

THE SEA-LEVEL CANAL.

Relation of the Canal Cut to Open Reservoir versus Artesian Reservoir.—The term " open reservoir " refers to that portion of the Floridian plateau wherein water, in cased wells, either penetrating the Ocala limestone or the upper series, on which part of the rainfall is absorbed and percolates downward to the reservoir, will not rise above the ground surface. The term " closed reservoir " refers to that portion wherein water will rise above the surface, in cased wells penetrating the Ocala limestone, or certain horizons in the upper series, through which any leakage is upward, and no water from rainfall directly enters the reservoir. It has been pointed out that the head on the artesian water, *i.e.*, the height above sea level to which it will rise, and the elevation of the water table in the open reservoir are both controlled by exactly the same mechanism—the head developed by accumulation of water in the water-table " highs " against the resistance offered by the rock to the flow of water through it to points of escape. It has also been pointed out that there is a great difference in the tenacity with which water is held in the Ocala limestone and in the upper series. The outcrop of the Ocala limestone at the surface, or over the area whereon there is extremely little cover other than sand, is shown in Fig. 3. On this figure is also shown the position of the sea-level contour at the top of the Ocala limestone—the position beyond which it dips below sea level.

Along the canal route this position is near the meridian of Silver Springs. Here the limestone plunges off steeply on a buried escarpment to nearly 30 feet below sea level. Had not the top of the Ocala limestone been removed here, prior to the deposition of the upper series, the inclination of its top would have been decidedly less, and the rock would have been cut by the canal excavation for

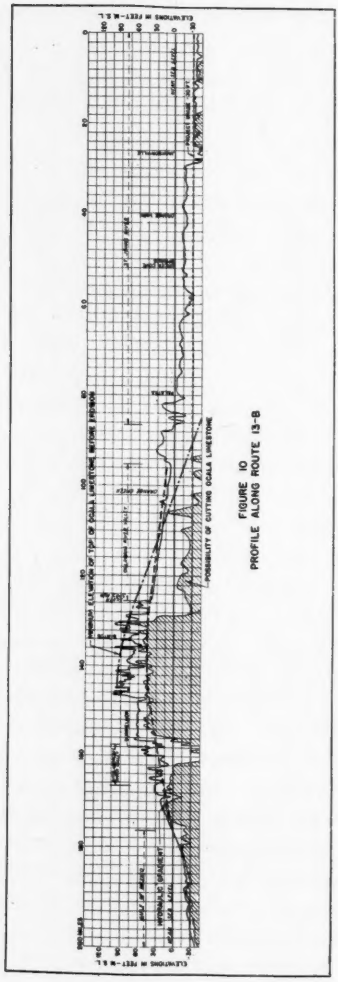


FIGURE 10
PROFILE ALONG ROUTE 13-B

some distance farther eastward than it will be under present conditions. (See Fig. 10.) The artesian head developed in the underlying Ocala limestone will raise water slightly above the level of Oklawaha River Valley. This is essentially the same as saying that cutting the Ocala limestone even below sea level along this part of the route is equivalent to cutting it above sea level in the open reservoir, for the water from it would flow into the canal under head, a contingency to be avoided if possible. Beyond the meridian of Silver Springs, the canal traverses, principally, formations of the upper series, entailing progressively shallower excavation, and, at the same time affording progressively deeper cover for the Ocala limestone, which plunges off to the northwest. The terrain is exceedingly wet on the whole and most of it at a very low elevation above the sea. No fears need be entertained that this portion of the cut will materially affect the water problem, other than very locally.

EFFECT OF THE CANAL ON WATER-TABLE SLOPES.

The "open reservoir" along the canal cut extends from the Gulf of Mexico to a point south-southeast of Silver Springs. The elevation of the water table along this section rises from zero at the Gulf to 45 feet, more or less, at the top of the low drainage divide, and descends to 40 feet near the meridian of Silver Springs, beyond which point it falls off to the east, controlled by artesian conditions along the canal route, for to the east the Ocala limestone dips beneath the upper series. Along this portion of the canal, from the Gulf to Silver Springs, the excavation will depress the top of the water table to an elevation near sea level, an elevation depending on how much fresh water runs out through the canal.

It is obvious that such a change in the position of the water table will initiate changes in the water-table gradients in the neighborhood of the canal.

The existing water-table slopes of the Florida Peninsula afford a sound basis on which to estimate the changes that may occur by reason of a canal cut.

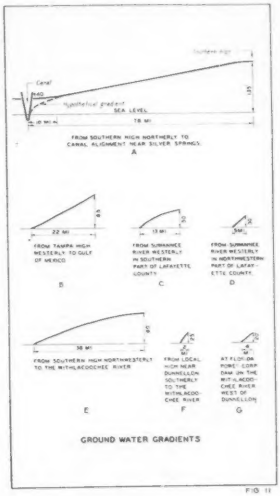
Any study of existing slopes, to be significant, should take into account the relative porosity of the formations affected, whether upper or lower series; the topography of the terrain; and the position of the gradient with reference to points of escape. It is obvious that the rise of the water table from the sea, inland, cannot exceed the rise of the land surface; that the slope along a ridge on the water table will be different from a slope down the sides of that water ridge; and that slopes solely in the upper series will be steeper than slopes in the lower series, other factors being equal. *Geologic processes have integrated all these elements.*

Consider the triangular area illustrated in Fig. 8. *A* lies at the apex of the triangle on the summit of the southern water "high" (135 feet above the sea); *B* lies at sea level at the Gulf entrance to the canal; *C* lies on the line of the canal south of Silver Springs.

The slope from *A* to *B* is 1.52 feet to the mile. The slope from *A* to *C*, at water-table elevation, is less, 1.21 feet to the mile. On digging the canal the water table immediately adjacent cannot fall more than 40 feet. It will actually be slightly less. With such a fall the slope *A–C* becomes 1.73 feet per mile, only 2½ inches per mile more than the gradient *A–B*. Now east of the point *C* the Ocala limestone plunges beneath sea level and in this direction the bottom of the canal will but slightly if at all cut the limestone; excavation being confined largely to the upper series.

How will the possible maximum fall of 40 feet in the water table at *C* be absorbed in the gradient *A–C*? On Fig. 11, a number of existing slopes are compared. Slope *A* lies north along the water-table ridge from the southern water-table "high" to the canal route near Silver Springs. Slope *B* descends from the top of the Tampa "high" to sea level; slopes *C* and *D* descend from the west side of the Suwanee River down to the water's edge; slope *E* descends from the southern "high" to the level of the Withlacoochee River; slope *F* is that of a small isolated high just east of Dunnellon; slope *G* is that south from the pool of the Inglis Dam. All of these slopes are very little different from the hypothetical slope that has been drawn from canal level at *C* to a point

about 10 to 15 miles south of the canal where this hypothetical slope meets the established gradient. The justification for drawing the gradient as pictured lies in the fact that where the water table falls to nearby free outlets, such a gradient actually appears at a number of places, as illustrated.


Canal
Hypothetical gradient
SEA LEVEL
78 MI.
FROM SOUTHERN HIGH NORTHERLY TO CANAL ALIGNMENT NEAR SILVER SPRINGS.
A
22 MI.
FROM TAMPA HIGH WESTERLY TO GULF OF MEXICO
B
FROM SUWANNEE RIVER WESTERLY IN SOUTHERN PART OF LAFAYETTE COUNTY
C
FROM SUWANNEE RIVER WESTERLY IN NORTHWESTERN PART OF LAFAYETTE COUNTY.
D
38 MI.
FROM SOUTHERN HIGH NORTHWESTERLY TO THE WITHLACOOCHEE RIVER
E
FROM LOCAL HIGH NEAR DUNNELLON SOUTHERLY TO THE WITHLACOOCHEE RIVER
F
AT FLOOD POINT CORPS DAM ON THE WITHLACOOCHEE RIVER WEST OF DUNNELLON
G
GROUND WATER GRADIENTS
FIG. 11

The triangular area *ABC* is worthy of consideration from a different point of view. The effect of cutting a canal from the Gulf to the point *C* insofar as the ultimate effect of ground-water level is concerned may be regarded as equivalent to revolving the area *ABC* on the axis *A–B* with the points *A* and *B* fixed in space, and the point *C* lowered 40 feet. The terrain along the line *A–B* is unaffected. The effects of the change are greatest at *C* but gradually diminish to the west toward the Gulf, since in this direction the original ground-water level falls off steadily to zero, while the effects also fall off toward the "high" at *A*, for in this direction the steepest slopes will certainly be near the canal, no matter what this slope may be.

For the present then it is postulated that after the canal is dug and the water table is adjusted, the 40-foot contour will lie south of the point *C* in the vicinity of Lake Weir, and curve off to the southwest to meet the present position of this contour where it crosses the Withlacoochee River. This conclusion is based on the study indicated above of hydraulic gradients observable today within the outcrop area of the Ocala limestone, coupled with the fact that the artificial canal-cut will traverse an area wherein resistance to flow water through the rocks will be substantially higher than in areas wherein underground drainage gradients have been during a long period reduced to graded slopes.

THE EFFECT OF THE CANAL ON WATER SUPPLIES.

Within the area of the open reservoir we are concerned only with the lowering of the top of the water table and the effects of this depression on (1) domestic water supplies, (2) agriculture, (3) unusual springs valued for their scenic beauty, (4) lakes.

Insofar as domestic water supplies for municipalities are concerned, no substantial injury will result from digging the canal. The largest city along the canal route within the area of the open reservoir is Ocala. At present there is not less than 1,600 feet of fresh water beneath sea level at Ocala. Even if this depth were materially reduced there would remain more than an ample supply for a much larger city than Ocala, and to the north of the city, at no great distance there will always be an enormously greater supply of underground water. Today the city is drawing its water principally from a depth of about 225 feet below sea level.

Shallow farm wells along the canal right-of-way between Dunnellon and Silver Springs may need deepening.

The progress of agriculture and the growth of vegetation in general are only remotely related to the position of the water table. Forests grow, crops are cultivated, and orange groves thrive on land whereunder the water table may be 60 or 100 feet beneath the surface. Lowering the water table further will not affect this

condition. Crops draw their nourishment from the rainfall as it wets the ground, and will do so in the future.

Plans for the canal provide that dams with properly designed water cut-offs will be constructed across Withlacoochee River, Blue Springs Run, Silver Springs Run, and Oklawaha River. In each instance, the water table elevation will be maintained at the crest of the dam, and water-table "humps" will be created exactly analogous to the water-table "hump" within Ocala limestone at the site of the Florida Power Corporation's dam west of Dunnellon. Neither Silver Springs nor Blue Springs will be injured.

It may be said at once that the domestic water supplies of such cities as Jacksonville, Tampa, Palm Beach, or Miami will be entirely unaffected by any changes in piezometric levels brought about by digging a sea-level canal.

The city of Tampa derives its water supply from the Hillsborough River, discharging surplus water from between the minor piezometric "high" north of the city and the main piezometric "high" of the lake region. Underground water from these "highs" flows slowly south to Tampa Bay, west to the Gulf of Mexico, and north and northwest toward outlets in the Gulf all the way north to the western end of the projected canal route, 50 miles distant. The slope of the water table from the summit of this "high" to the mouth of the Withlacoochee River will not be changed by the canal-cut; and any changes in the slope of the water table from the canal-cut farther inland to the summits of these "highs" will be absorbed long before the positions of the "highs" are reached. Much of the drainage basin of the Withlacoochee River and the lake system bordering it lies between the canal and these "highs."

The city of Palm Beach derives its domestic water supply from rainwater stored in lakes and swamps, the Quaternary sands, and sandy limestones exposed at the surface of the ground. The Ocala limestone lies buried 900 feet, more or less, beneath the surface, and even if the water within it were potable, which it is not, the artesian head of such water would be unaffected by the

canal-cut 200 miles distant. There is no connection physically between the potable water supplies of Palm Beach and the ground-water reservoir that will be traversed by the canal.

The city of Miami is even farther to the south, 250 miles distant from the canal. The water supplies of this place are also derived from the Quaternary limestone, known as the Miami Oolite, at the surface, and the Ocala limestone here is buried 1,000 feet, more or less, and does not contain potable water. Local rainfall is the source of potable water at Miami as at Palm Beach.

The city of Jacksonville obtains its water supplies from deep wells under artesian head derived from the piezometric "high" in the terrain to the west and northwest of the city. The city is 75 miles distant from the nearest point on the canal line where the Ocala limestone will be cut and from Lake George where the piezometric surface is close to sea-level. No change is to be expected in the head of the artesian wells at Jacksonville because of the canal-cut.

The city of Sanford is 52 miles from the canal-cut near Silver Springs. It obtains its artesian water entirely from the northeastern slope of the southern "high," and not from the area to the northwest where the Ocala limestone occurs at the surface. (Fig. 8.) The artesion heads are already reduced nearly to sea level in the Lake George region, northward from the city. The wells at Sanford are already affected by bottom-water salting. They cannot be affected except by a reduction of the water table in the southern "high," which is not to be expected from the construction of the canal. Therefore the canal-cut will have no appreciable effect on the water supply of Sanford.

Ocala, Florida,
May, 1936.

PECULIAR HYDROTHERMAL COPPER-BEARING VEINS OF THE NORTHEASTERN COLORADO PLATEAU.*

RICHARD P. FISCHER.

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INTRODUCTION.

THE present investigation was undertaken in connection with general studies of the "Red Beds" copper deposits in the southwest, the vanadium-uranium deposits of western Colorado and eastern Utah and the silver-bearing sandstones at Silver Reef, Washington County, Utah. All of these deposits have certain

* Presented before the Society of Economic Geologists, New York Meeting, Dec. 26, 1935.

features in common.[1] Although mineralization at the Cashin mine[2] has heretofore been attributed to circulating meteoric waters and classified as a "Red Beds" deposit it is apparent that it and the other copper-bearing vein deposits described in this paper are not related to this type of mineralization. The writer hopes to publish, at a later date, the results of his studies of the bedded sandstone ores. It is not, however, within the scope of the present paper to attempt to show why these vein deposits are not related to the "Red Beds" deposits, although this point will be obvious to those acquainted with the typical "Red Beds" mineralization. Rather, it is thought that the peculiar mineralization to be described merited this separate note.

The ore samples used in this study were collected almost entirely from the mine dumps. Time and the condition of the mines did not permit detailed studies underground. The geology and ore occurrence at the Cashin mine was described by Emmons[3] in 1905, and Coffin[4] in 1921 gave a brief description of this mine and the related deposits in western Colorado.

Location and General Geology.—The location of the deposits to be described is shown on Fig. 1. They lie essentially in an arc or semi-circle peripheral to the La Sal Mt. laccoliths. Five of these mines, namely: the Cashin, Cliffdweller, Sunrise and Copper Rivet mines in Colorado and the Hoosier mine in Salt Valley, Utah, were studied by the writer. Other mines indicated on the map were not visited but from the information available they appear to be related.

The region surrounding the La Sal Mts. is the highly dissected part, "the Canyon Lands," of the Colorado Plateau Province. Sedimentary rocks consist of Pennsylvanian and Permian shales

[1] Lindgren, W.: Copper, silver, lead, vanadium and uranium ores in sandstone and shale. ECON. GEOL., vol. 6, pp. 568–581, 1911. Ore deposits of the Western States, Hess, F. L., pp. 452–480, Finch, J. W., pp. 481–487. Am. Inst. Min. Met. Eng., 1933.

[2] Emmons, W. H.: The Cashin mine, Montrose County, Colorado. U. S. Geol. Surv. Bull. 285, pp. 125–128, 1905. Lindgren, W.: Mineral Deposits. P. 406, 1933.

[3] Emmons, W. H.: *Op. cit.*

[4] Coffin, R. C.: Radium, uranium and vanadium deposits of southwestern Colorado. Colo. Geol. Surv. Bull. 16, pp. 219 and 220, 1921.

with interbedded limestone, gypsum and local salt deposits overlain by the massive sandstones and shales of Mesozoic age. Intrusive igneous rocks are apparently confined to the diorite porphyry laccoliths of the La Sal Mts. and a small pluglike body of soda trachyte in Castle Creek Valley (Fig. 1). It will be noted that none of these intrusives occur in close proximity to the copper deposits.

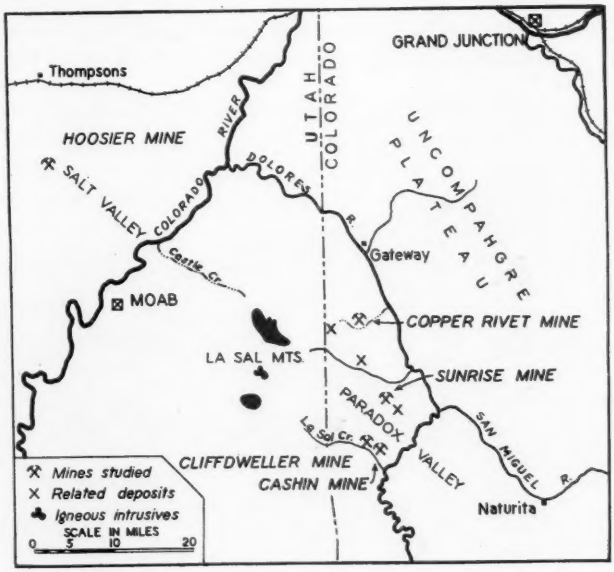


FIG. 1. Index map showing the location of the deposits.

ORE DEPOSITS.

Production.—According to the reports of the Colorado State Bureau of Mines (1897–1904) and to Mineral Resources (1905–1931) the total production for Montrose and Mesa counties, Colorado amounts to 216,030 ounces of silver and 569,951 pounds of copper. A small amount of placer silver is included in these

figures. The Cashin mine has been the greatest producer in this region. Emmons says of this mine:[5]

> According to the books of the La Sal Copper Mining Company, the present owners, it has produced altogether 363,778 ounces of silver and 732,740 pounds of copper. These figures do not include the shipments of native copper, of which no record was available.

Mineralization.—Mineralization is of the fissure vein type and occurs along normal faults of small displacement, the ore developing best in the lower part of the massive and competent Wingate[6] sandstone where these fractures formed gaping fissures. Fig. 2

FIG. 2. View of the northeast wall of Paradox Valley showing the massive Wingate sandstone cut by the Sunrise fault (indicated by arrow). The Sunrise mine lies at the base of the vertical cliff.

[5] Emmons, W. H.: *Op. cit.*, p. 125 .

[6] This is the massive sandstone in the upper part of the "Dolores formation" of Coffin.[7] In 1926 J. B. Reeside, Jr., and C. E. Dobbin visited Sinbad and Paradox valleys and suggested this correlation.[8]

[7] Coffin, R. C.: *Op. cit.*, pp. 46–61.

[8] Gilluly, J., and Reeside, J. B., Jr.: Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah. U. S. Geol. Surv. Prof. Paper 150, p. 69, 1928.

shows the Wingate sandstone, about 300 feet thick, on the northeast wall of Paradox Valley where it is cut by the Sunrise fault. The mine lies at the base of the vertical cliff.

The primary ore minerals consist principally of sulphides of copper. Luzonite is common in the five deposits studied. Sphalerite and galena are abundant in the ore from the Cashin and Cliffdweller mines. Copper arsenides with native copper were found in the Cashin ore. Of particular interest are the metacolloidal intergrowths and colloform structures which in places are well developed. The gangue consists of dolomite, calcite and barite. The ore minerals locally replace the sandstone wall rock but generally occur with the gangue as a fissure filling.

It will be noted that no silver minerals were observed in this investigation. This is surprising in view of the fact that the principal value of the ores as mined was silver. It is reported[9] that rich bodies of native silver and argentite were found during the early development of the Cashin mine. Apparently some of the primary sulphide minerals are highly argentiferous.

CASHIN MINE.

The Cashin mine is located on La Sal Creek about 4 miles above its junction with the Dolores River. The creek at this point has cut a canyon nearly a thousand feet deep. The camp and the mill were built on a narrow alluvial plain. An adit, with its portal about 40 feet above the stream bed, follows the vein on the north side of the creek. Coffin,[10] who visited the mine in 1919, reports that this adit is more than 1,700 feet long.

Mineralization.

The ore deposit occurs along a fault that cuts the Wingate sandstone. This fault strikes about N. 40° E. and dips 65° N.W., causing a displacement of about 20 feet. The fracture can be traced northeast for a mile and a half to the rim of the Paradox Valley. Some prospecting has occurred in this direction but without satisfactory results.

[9] Emmons, W. H.: *Op. cit.*, p. 126.

[10] Coffin, R. C.: *Op. cit.*, p. 219.

Emmons, who was the first to give a geologic description of this deposit, says:[11]

> The lode varies in width from 1 foot to 20 feet or more. . . .
>
> Rich ore, composed largely of argentiferous covellite, chalcocite, and bornite and also carrying calcite and barite, occurs as veinlets in the fissure zone. These veinlets are from 1 inch to several inches wide and are sometimes composed entirely of the copper sulphides, the brilliant blue of the covellite contrasting strongly with the dark chalcocite and making an ore of unusual beauty. The veinlets are generally approximately parallel to the direction of the fissure, but sometimes cut diagonally across it. Where the lode is widest, there are four or five of these veinlets. Frequently they play out along a narrow seam, perhaps to reappear beyond. Carload shipments of the rich ore have given returns as high as 512 ounces of silver to the ton. Large masses of the native copper occur embedded in the kaolin, especially in the lowest level. Most of them are irregular bodies about as thick as they are long, and one was found which weighed over 500 pounds. . . . Native copper also occurs in veinlets with calcite and barite, and one shipment averaged 89 per cent copper and 77 ounces of silver to the ton.

Three types of ore were found on the dumps of the Cashin mine. The first to be described, the *sandstone replacement* type of ore, is composed principally of chalcopyrite. This ore occurs as irregular masses in the sandstone and probably represents replacement along fractures. No gangue minerals were noted in specimens of this ore. The second, or *vein filling* type of ore, consists of a breccia of early ore minerals and fragments of the sandstone wall rock cemented by a gangue of crystalline dolomite. Late ore minerals cut the gangue and the breccia. Replacement of the sandstone fragments and the wall rock is negligible. The third type, which is not abundant on the dumps, consists of *native copper* with *copper arsenides* in a gangue of fibrous barite and crystalline calcite. Unfortunately, the relationships among these types of ore are not known to the writer.

[11] Emmons, W. H.: *Op. cit.*, pp. 126 and 127.

Sandstone Replacement Type of Ore.

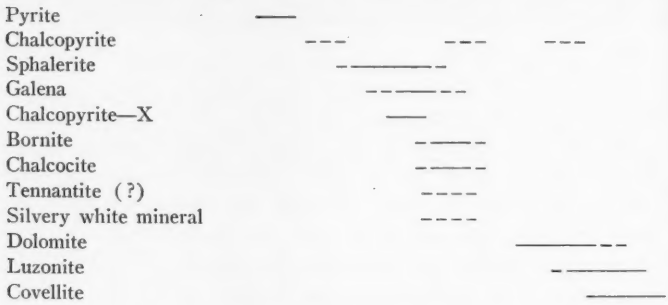
This ore consists of chalcopyrite which has largely or wholly replaced the sand grains and which in turn has to a greater or less extent been replaced by covellite. Hand specimens of this material range in color from a dull yellowish gray to a dirty bluish gray, depending upon the amount of covellite present. A little sphalerite is intimately associated with the chalcopyrite, but the age relationships are not clear.

Typically, covellite occurs in the chalcopyrite as short bladed aggregates. Although the total amount of covellite varies somewhat from place to place, its development is remarkably uniform throughout the chalcopyrite. Certainly the growth of these covellite aggregates has neither been controlled by grain boundaries nor mineral contacts. Covellite is as abundantly developed in the center of a large mass of chalcopyrite as it is along the contacts of the chalcopyrite with sphalerite or with the sand grains. Even the small grains and cross-cutting veinlets of chalcopyrite in sphalerite seem to carry their share of covellite, no more or no less than the larger areas of chalcopyrite (Fig. 3).

Vein Filling Type of Ore.

Crystalline dolomite fills the veins and cements a breccia of early ore minerals that consist of intimately associated sphalerite, galena, pure chalcopyrite and an intergrowth of chalcopyrite with mineral X. A few specimens of this ore carry bornite and chalcocite. Chalcopyrite, tennantite (?) and an unknown silvery white mineral are finely intergrown with the bornite and chalcocite. Later luzonite and covellite cut and replace the gangue and the earlier ore minerals. The vein filling is quite porous and small vugs and open fractures are common. Dolomite crystals line these openings and are commonly coated by small botryoidal masses of luzonite.

The following paragenetic sequence is offered for this type of ore. As will be pointed out later the age relationships among the early ore minerals are largely inconclusive.



Pyrite is all but absent in the Cashin ore. It occurs only in small scattered grains which have been veined and partially replaced by the surrounding minerals.

Chalcopyrite, although not abundant in this type of ore, is widely distributed, and its deposition apparently took place throughout the period of mineralization. Early chalcopyrite occurs as small grains in sphalerite and galena and as residual fragments in some of the masses of the chalcopyrite-X intergrowth. Later chalcopyrite is intimately intergrown with bornite and chalcocite; and it again formed at the time of luzonite deposition. All this chalcopyrite differs markedly from that occurring in the sandstone replacement type of ore in that it is not intergrown with covellite.

Sphalerite and Galena.—Sphalerite is the most abundant metallic mineral in this type of ore. It plays, essentially, the rôle of host to the later ore minerals.

Galena is abundant and its manner of occurrence is varied. With sphalerite it may form grains showing mutual boundary relationships, irregular replacement veinlets, or metacolloidal intergrowths exhibiting a colloform structure. A single grain of galena may show mutual boundaries against sphalerite on one side and on the opposite side it may send narrow veinlets of wholly irregular direction into the zinc mineral. Such replacement veinlets are shown in Fig. 4. In places elongate or tabular tongues of galena project into the sphalerite. Charac-

teristically these tongues are parallel and are quite regularly spaced. It is not uncommon to find a single grain of galena (shown by the perfect orientation of the cleavage pits) apparently cut by irregular veinlets of sphalerite.

Metacolloidal intergrowths of sphalerite and galena are common. Where best developed they possess a center or core composed of sphalerite with elongate blebs of galena radiating outward (Fig. 5). These structures are partially enclosed by one or more concentric bands of galena in which blebs of sphalerite that exhibit a roughly radial orientation are embedded. (Fig. 6).

From the Republic mine of the New World (Cooke City, Mont.) district Lovering has described a sphalerite-galena intergrowth in which " sphalerite forms an embedding mass in which blebs and lines of galena radiate from many centers toward concentric galena borders." [12] He concluded that these structures were formed from colloidal solutions. The central areas of the colloform masses found in the Cashin ore are remarkably similar to those described and illustrated by Lovering.

Chalcopyrite-X Intergrowth.—An extremely fine grained graphic intergrowth of chalcopyrite with some unidentified mineral is abundantly developed in this ore. The intergrowth may occur in small isolated fragments in the gangue or in relatively large irregularly shaped masses. In hand specimen this material has a dull olive brown color. When cut by a knife the smooth surface possesses a reddish tinge, suggesting bornite.

So fine grained is this intergrowth that in polished sections even with the highest magnification the components are all but indistinguishable. However, the strong pleochroism and anisotropism of the unknown mineral clearly shows a triangular grid pattern. Being so fine grained, the intergrowth must be treated as a whole. It is distinctly pleochroic, ranging from pale yellow to deep pink or rose. Anisotropism is strong, changing from a brick red to a greenish gold, each color appearing twice in a complete revolution of the stage. Because of the fine grained texture, etch reactions are unsatisfactory. Spectographic analysis

[12] Lovering, T. S.: The New World or Cooke City mining district, Park County, Mont. U. S. Geol. Surv. Bull. 811–A, p. 81, 1930.

shows the presence of only copper and iron, sulphur being too volatile to determine by this method. Blow pipe tests for arsenic proved negative.

Covellite replaces this intergrowth to a greater or less extent. Generally this replacement works into the intergrowth from grain boundaries and mineral contacts, or outward from some nucleus within the intergrown mass. In the first stage of this replacement long delicate needles of covellite develop. These needles accentuate the grid pattern and are apparently oriented along crystallographic planes (Figs. 7, 8). If this process continues feathery aggregates of covellite develop, destroying the grid structure as the chalcopyrite adjusts itself to the grain pattern of the covellite. Mineral X is apparently replaced.

In one of the polished sections studied minute blebs of a reddish mineral intergrown with chalcopyrite were noted in the midst of the graphic intergrowth. Optically these grains closely resemble the intergrowth. They are strongly pleochroic, ranging from dull gray to bornite red. Anisotropism is strong, varying from deep brick red to light blue- or gray-green twice during a complete revolution of the stage. The mineral is negative to common reagents except KCN which quickly stains it irridescent to black. The blebs are too fine grained to attempt analysis.

Of the common ore minerals this unknown more nearly resembles luzonite. It is, however, distinctly pleochroic and more strongly anisotropic. What appears to be the same intergrowth was found in a copper-lead ore described by Snelgrove[13] from the Sops Arm area, Newfoundland. He tentatively identified the unknown mineral as luzonite.

In some sections of the Cashin ore this intergrowth was seen cutting and replacing masses of pure chalcopyrite. It is in turn cut and replaced by veinlets of chalcopyrite, which develop with luzonite. The intergrowth in many cases is so intimately associated with galena that age differences have not been determined. In places, veinlets of this intergrowth cut sphalerite, but elsewhere the relations suggest that the zinc mineral is later than and re-

[13] Snelgrove, A. K.: Geology of gold deposits of Newfoundland. Newfoundland Dept. Natural Res., Geol. Section, Bull. 2, p. 41, 1935.

places it. The intergrowth was not seen in contact with bornite and chalcocite.

Bornite and Chalcocite.—Bornite and chalcocite are not important ore minerals in the Cashin ore, judging from the specimens collected from the dumps. In general, however, when present they are abundantly developed. Rarely a little chalcocite may occur in sections without bornite, but bornite without chalcocite was not noted.

Bornite and chalcocite are intimately associated with sphalerite and galena and occur as interlocking grains of varying sizes and as irregular replacement veinlets of one mineral in another. Evidences of age differences are for the most part inconclusive. Generally bornite and chalcocite appear to replace sphalerite, each cutting the zinc mineral with a network of veinlets which connect small replacement masses. It is not uncommon, however, to find rather persistent veins of sphalerite which appear to cut and partially replace the two copper minerals. There is nothing to suggest age differences between bornite and galena. Either may occur without the other or both may be finely intergrown, the contacts being of the mutual boundary nature. Where these two minerals are intergrown, bornite may be in excess of galena or vice versa. Chalcocite and galena relations are likewise extremely intimate. Generally the two minerals exhibit mutual boundary contacts, but fine grained intergrowths of galena in chalcocite are common (Fig. 9). Bornite and chalcocite occur together in rounded interlocking grains. Neither cuts the other and it is impossible to say that one is younger or replaces the other. No graphic or subgraphic intergrowths were noted, however.

Chalcopyrite is rather abundant in the bornite and occurs as small irregular grains and as cigar-shaped blades. Locally these blades develop parallel to one another and occasionally blades of different orientation are seen in contact, but nowhere was a true lattice texture found. Bornite, when etched with nitric acid, shows a "crackled porcelain" structure.

Two types of chalcocite were noted in these specimens, a fine

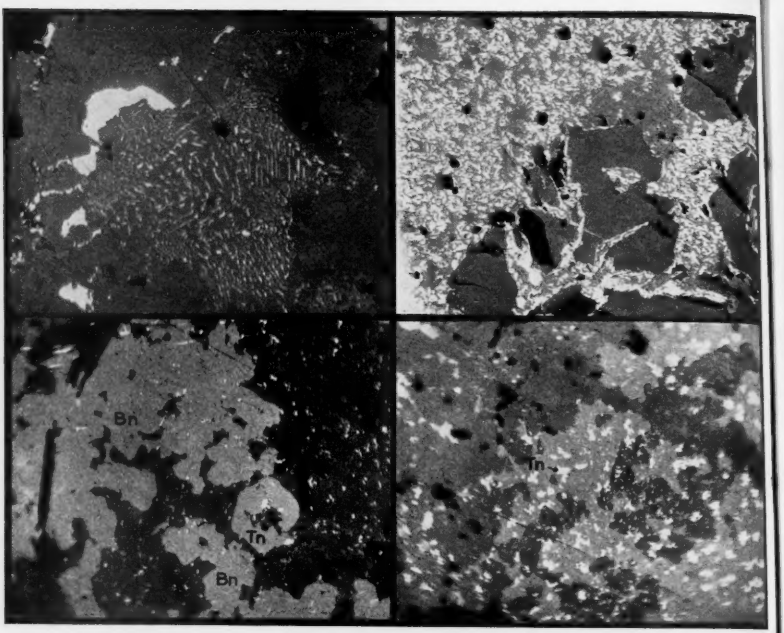


FIG. 9. Intergrowth of galena (white) and chalcocite (gray). ×365. (Oil immersion.)

FIG. 10. Intergrowth of chalcopyrite (white) and chalcocite (light gray) cutting sphalerite (dark gray). ×120.

FIG. 11. Tennantite (?) (Tn) and unknown silvery white mineral (white) in chalcocite (dark gray) and bornite (Bn). Covellite (black) is scattered through the section. This figure shows one of the larger grains of tennantite (?) and the typical development of the silvery white mineral. ×365. (Oil immersion.)

FIG. 12. Tennantite (?) (Tn) with unknown silvery white mineral (white) in chalcocite (light gray) and sphalerite (dark gray). ×365. (Oil immersion.)

and a coarse grained variety. The fine grained variety predominates. It exhibits a "crackled porcelain" structure when etched and is apparently isotropic. This type of chalcocite is intimately associated with the other ore minerals as noted above.

Chalcopyrite, tennantite or tetrahedrite (the former being more likely because of the known presence of arsenic in the ore) and an unknown silvery white mineral are disseminated through the fine grained chalcocite. The chalcopyrite occurs either in grains about a hundredth of a millimeter across (Fig. 10) or in hair-like veinlets of wholly irregular direction. Tennantite (?) and the unknown silvery white mineral are intimately associated in the chalcocite and bornite and in places in the sphalerite. They occur in minute grains, generally only a few thousandths of a millimeter across. A few larger grains of tennantite (?) were seen, the largest being about .03 of a millimeter in cross section. The silvery white mineral is too fine grained to attempt identification (Figs. 11 and 12).

The second type of chalcocite is coarse grained, the grains often being a half millimeter in diameter. It is anisotropic and shows orthorhombic cleavage even on freshly polished sections. It appears to replace the fine grained chalcocite. Chalcopyrite, tennantite (?) and the unknown silvery white mineral are entirely absent in the coarse grained chalcocite.

The occurrence of hypogene chalcocite is always interesting. Lacking definite criteria the following evidence suggests, in the mind of the writer, that the fine grained chalcocite is hypogene:

1. "Group replacement": Schwartz[14] states that the replacement of one mineral by several simultaneously is dependable evidence of hypogene origin. In this case sphalerite is cut and replaced by galena, bornite, and chalcocite, the three minerals occurring in the host in essentially the same structural and textural habits. As pointed out above, there is not the slightest evidence of age differences among these three minerals.

2. Replacement independent of fracturing: This has been suggested by Bastin and Laney[15] as substantiating evidence of hypogene origin.

[14] Schwartz, G. M.: Microscopic criteria of hypogene and supergene origin of ore minerals. ECON. GEOL., vol. 27, p. 537, 1932.

[15] Bastin, E. S., and Laney, F. B.: The genesis of the ores at Tonopah, Nevada. U. S. Geol. Surv. Prof. Paper 104, p. 25, 1918.

3. Granular texture and interlocking grains: Galena, bornite, and chalcocite occur in this manner.

4. The uniform distribution of the scattered minerals (tennantite (?) and the unknown silvery white mineral) in the hosts (chalcocite, bornite and adjacent sphalerite) suggests that the scattered minerals are hypogene, in which case the host minerals are hypogene.

5. Complete absence of evidence of supergene enrichment.

Luzonite and Covellite.—These are the latest of the primary minerals in this type of ore. Although much of the covellite is probably later than the luzonite, in part they seem to be contemporaneous.

Luzonite occurs in veinlets and replacement masses in the earlier ore minerals, in rude colloform bands in covellite, but it is most commonly developed in colloform masses along the walls of cavities and open fractures. Here the luzonite masses are commonly coated by dolomite crystals, but in places it is clear that the luzonite formed on the gangue crystals that line these cavities. No luzonite was seen in the specimens containing chalcocite and bornite.

Considerable chalcopyrite developed at this stage of mineralization and intimate intergrowths of luzonite and chalcopyrite are common (Figs. 13, 14 and 15). Where chalcopyrite is the predominant constituent of the intergrowth (Fig. 13) luzonite occurs in minute curved needles. Where luzonite predominates (Fig. 14) thin bands of chalcopyrite border a crystal or an aggregate of several luzonite crystals. Roughly concentric bands of chalcopyrite in the colloform masses of luzonite show similar structure (Fig. 15).

Covellite is abundant in the Cashin ore and its manner of occurrence is varied. Hand specimens of massive covellite were found on the dumps. These consist of coarsely crystalline covellite and irregular veinlets or masses of finely crystalline covellite. The two varieties are often separated by a narrow band of chalcopyrite or by a broader band of luzonite, resembling in many cases some of the structures developed in the Kennecott covellite

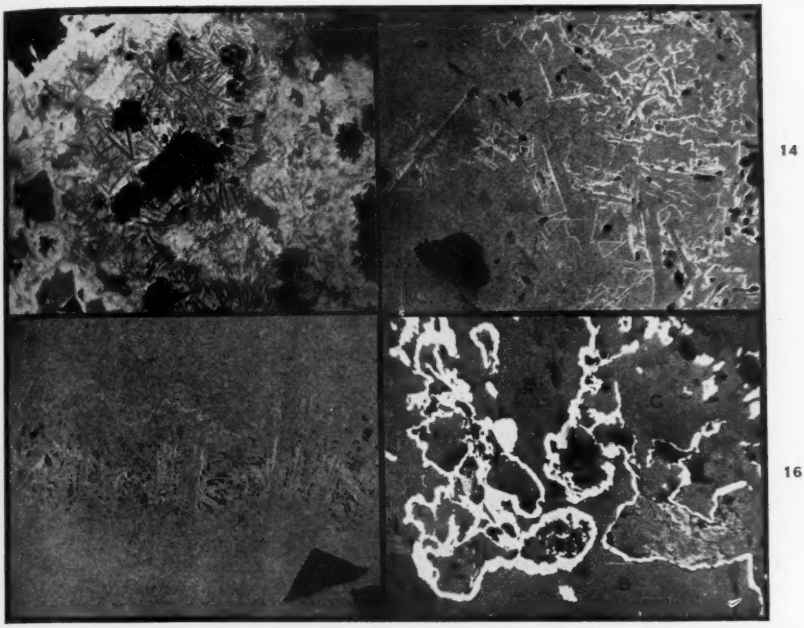


FIG. 13. Intergrowth of luzonite (gray) and chalcopyrite (white). This pattern develops where chalcopyrite is the predominant constituent of the intergrowth. The black areas are holes in the surface. × 365. (Oil immersion.)

FIG. 14. Intergrowth of luzonite (gray) and chalcopyrite (white). This pattern develops where luzonite is the predominant constituent of the intergrowth. × 138.

FIG. 15. Bands of chalcopyrite (white) in colloform masses of luzonite (gray). The dark gray masses in the lower right hand corner of the figure are dolomite crystals. × 76.

FIG. 16. Copper arsenides (white) bordering and cutting crystalline calcite (*C*) with interstitial fibrous barite (*B*). × 76.

ore.[16] In addition, veinlets of covellite cut the dolomite gangue and the earlier ore minerals and rims of covellite border the brec-

[16] Lasky, S. G.: A colloidal origin of some of the Kennecott ore minerals. ECON. GEOL., vol. 25, p. 750, Fig. 5, 1930.

ciated fragments of the early ore minerals. These rims range up to one-sixteenth or one-eighth of an inch in thickness on the coarser fragments of the ore breccia. They develop principally by replacement of the gangue; the covellite forming as coarse grains, which stand normal to the ore fragments. Also, narrow blades and small feathery aggregates of covellite occur sparsely disseminated through the various ore minerals or develop along mineral contacts.

Ore-breccia and Ore-gangue Relationships.—Relations between the early ore minerals and the gangue are peculiar. It seems impossible to explain these except by assuming that the early ore minerals preceded the dolomite. In the specimens studied, sphalerite with associated early chalcopyrite, galena and the chalcopyrite-X intergrowth, occur as a breccia of isolated fragments scattered in the dolomite gangue, the fragments varying in size from minute particles to masses several inches across. The smallest particles may be composed of a single mineral or two or more minerals intimately associated.

In hand specimens it was noted that some of the larger ore fragments have been cut by dolomite veinlets. Thin and polished sections show that the contact of the dolomite with these ore minerals is extremely irregular. Generally the ore minerals appear corroded, with the dolomite advancing in a series of ragged convex curves. It is not uncommon to find, however, rectangular or tabular masses of the gangue projecting into a mass of ore minerals. With crossed nicols it was noted that these tabular masses are mostly composed of several crystals of dolomite, oriented entirely independently of one another. Such structures are interpreted as dolomite pseudomorphs after an earlier gangue mineral. Again, in rare cases, blades or splinters of sphalerite and other ore minerals, with a parallel or roughly fan-like orientation, were observed in the holocrystalline gangue. Similar patterns are common where ore minerals have formed in a mass of platy barite. It is thought that these relationships suggest that the dolomite has replaced barite.

Luzonite and covellite are the only ore minerals that actually cross-cut the gangue. The colloform masses of luzonite that develop in cavities and open fractures, in part forming on the lining of dolomite crystals, have already been described. Also, mention has been made of the aureoles of covellite that rim the fragments of the ore breccia, replacing the gangue. These relations stand in sharp contrast to the relations of the dolomite with the earlier ore minerals.

The following hypothesis is offered; The early ore minerals originally formed a rather compact vein filling. These minerals were deposited with or replaced an unknown gangue mineral, probably barite. This ore was then shattered, possibly by movement along the Cashin fault. The resulting breccia, composed of ore minerals and fragments of sandstone wall rock, was cemented by dolomite, this gangue apparently partially replacing the ore minerals and entirely replacing the earlier gangue. This was followed by the deposition of luzonite and covellite.

Native Copper and Copper Arsenide Type of Ore.

These minerals occur with a gangue of fibrous barite, which developed interstitially to masses of crystalline calcite. Fig. 16 shows the typical occurrence of the arsenides as well as much of the native copper. The metallic minerals form along the contact of the barite and calcite and send irregular veinlets into the calcite masses. In form this occurrence closely resembles the " tubercle textures " described by Bastin [17] in the arsenide ore of Cobalt, Ont. In places the native copper becomes more massive and this texture is destroyed.

The copper arsenides form an extremely complex mixture and no detailed study was made of them. The age relationship between the arsenides and the native metal has not been satisfactorily established.

The origin of the native copper and the arsenides cannot be determined definitely with the meager information at hand. Evi-

[17] Bastin, E. S.: Primary native silver ores of South Lorraine and Cobalt, Ontario. Econ. Geol., vol. 20, pp. 1–24, 1925.

dence, however, suggests that these minerals were deposited from hypogene solutions. Coffin observes that "the position of sulphides and native copper is reversed from the usual arrangement, in that the native copper generally occurs lower down in the fissures than the copper sulphides."[18] According to Mr. Frank Wilson[19] of Naturita, Colorado, the native copper was found in the "Red Beds," which means the red Dolores sandstones and shales below the Wingate sandstone. The presence of hypogene native copper in rocks rich in ferric oxide is common enough to pass without discussion.

CLIFFDWELLER MINE.

The Cliffdweller mine is located on La Sal Creek about a mile above the Cashin mine. Developed ore occurs in the Wingate sandstone along a normal fault that strikes N. 26° E. and dips about 70° to the east. Displacement along this fracture is about 20 feet. Mineralization is essentially the same as at the Cashin mine and will not be discussed.

SUNRISE MINE.

The Sunrise mine is located on the northeast wall of Paradox Valley about 4 miles northeast of the village of Paradox. It lies about 600 feet above the general level of the valley and at the base of the sheer cliff formed by the Wingate sandstone (Fig. 2).

At this point a fault, striking N. 35° E. and dipping to the southeast about 80°, cuts the sedimentary rocks. Displacement is normal, the beds on the hanging wall side dropping about 35 feet. The fault is essentially a brecciated zone, ranging from a foot to several feet in width.

Development consists of two adits, one 80 feet above the other. The lower adit is caved at a point about 300 feet from the portal, and the upper one is in the same condition about 50 feet from the entrance. These adits follow the vein along the fault. In several places the ground above and below the lower level has been stoped.

[18] Coffin, R. C.: *Op. cit.*, p. 219.

[19] Oral communication.

Mineralization.

There is an interesting variation in the ore from the two adits. In the upper level the primary ore consists principally of massive chalcopyrite with lesser amounts of chalcopyrite intergrown with bornite and luzonite. Ore from the lower adit is composed of massive chalcocite which fills the veins and open fractures, with or without a gangue of barite and calcite.

Both types of ore are replaced to a greater or less extent by oxidized minerals; the chalcopyrite ore by "copper pitch," iron oxide and malachite, the chalcocite ore by malachite and "copper pitch."

Optical studies reveal the following ore minerals:

	Primary	Secondary
Chalcopyrite	x	
Bornite	x	
Luzonite	x	
Chalcopyrite-X	x	
Chalcocite	?	x
Covellite		x
"Copper pitch"		x
Iron oxide		x
Malachite		x
Azurite		x
Chrysocolla		x

Chalcopyrite and Chalcopyrite Intergrowths.—The massive chalcopyrite from the upper level appears to have replaced the sandstone, probably adjacent to fractures. It has been brecciated and largely replaced by later minerals. Chalcocite was the first of these replacing minerals. It entered the host along fractures and sent long narrow tongues into the fragments. Later "copper pitch" worked out from the same fractures, replacing the chalcocite and the chalcopyrite.

Small masses of the chalcopyrite-X intergrowth, so common in the Cashin ore, were noted in the chalcopyrite in one section.

Nodular or botryoidal masses of bornite with concentric bands of chalcopyrite and colloform intergrowths of chalcopyrite with luzonite are commonly developed in this ore. These masses generally range from a quarter to a half inch or more in cross section.

Apparently they formed in cavities or open fractures. These masses have been more or less replaced by "copper pitch." Bornite and especially luzonite are more susceptible to this replacement than chalcopyrite, and beautiful examples of selective replacement are to be noted.

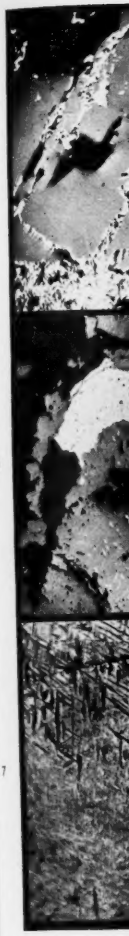
Botryoidal masses of bornite are shown in Fig. 17 and Fig. 18 is a photomicrograph of another section showing the narrow and irregular but always concentric bands of chalcopyrite that develop in these masses. Bornite is always more abundant than chalcopyrite and forms from 80 to 90 per cent. or more of the original structure.

In the chalcopyrite-luzonite intergrowths chalcopyrite is the predominant mineral. Bands or rings of pure chalcopyrite alternate with bands of luzonite intergrown with chalcopyrite (Figs. 19, 20 and 21). In the latter case chalcopyrite is interstitial and luzonite occurs in minute curved or scimitar-shaped blades. These curved blades are oriented essentially radially to the center of the colloform structure.

The selective replacement of luzonite by "copper pitch" is well shown in the photomicrographs. The centers of these colloform masses are in all cases largely replaced by "copper pitch." Generally, however, remnants of luzonite, without chalcopyrite, occur in these areas (Fig. 19). Generally, where the colloform masses are cut by "copper pitch" veinlets, "bays" are formed in the chalcopyrite-luzonite bands and the bands of pure chalcopyrite project as rounded promontories into the veinlets (Fig. 20). In favorable places the curved blades of luzonite are faithfully pseudomorphed by "copper pitch" (Fig. 21).

Chalcocite.—The ore from the lower level is composed of almost solid chalcocite. In one section minute fragments of bornite were noted in the chalcocite. Small grains of chalcopyrite were seen where chalcocite replaces calcite. A little covellite replaces the chalcocite. The ore has been to some extent replaced by malachite and "copper pitch."

The chalcocite forms a massive compact vein filling or replaces the gangue. It occurs in coarse interlocking grains, the grains



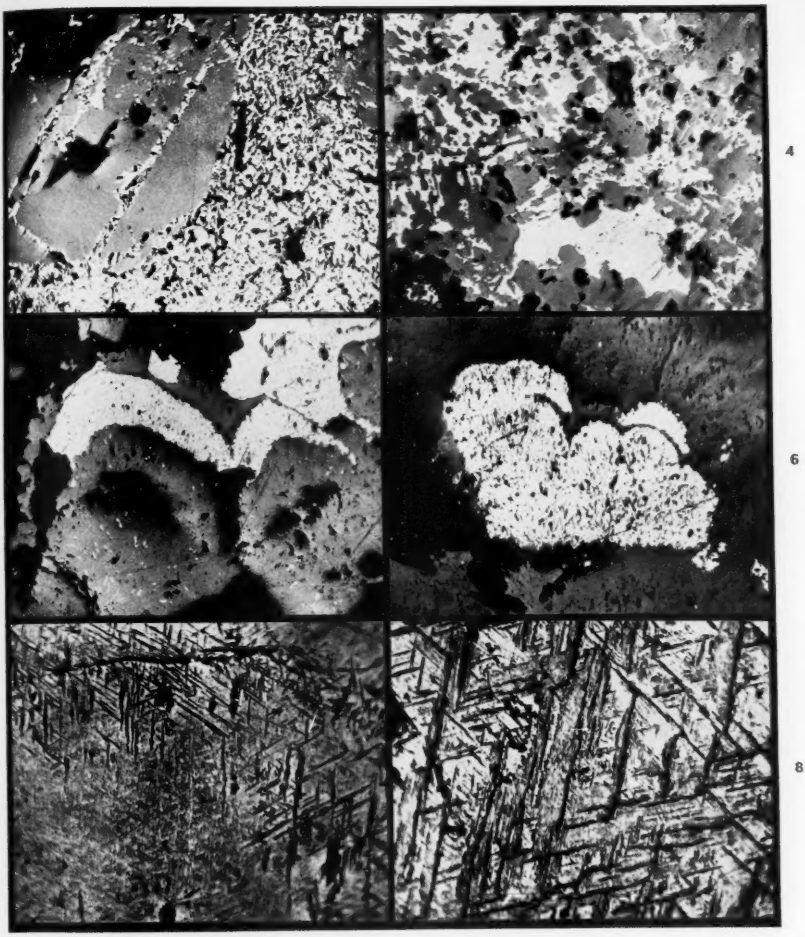
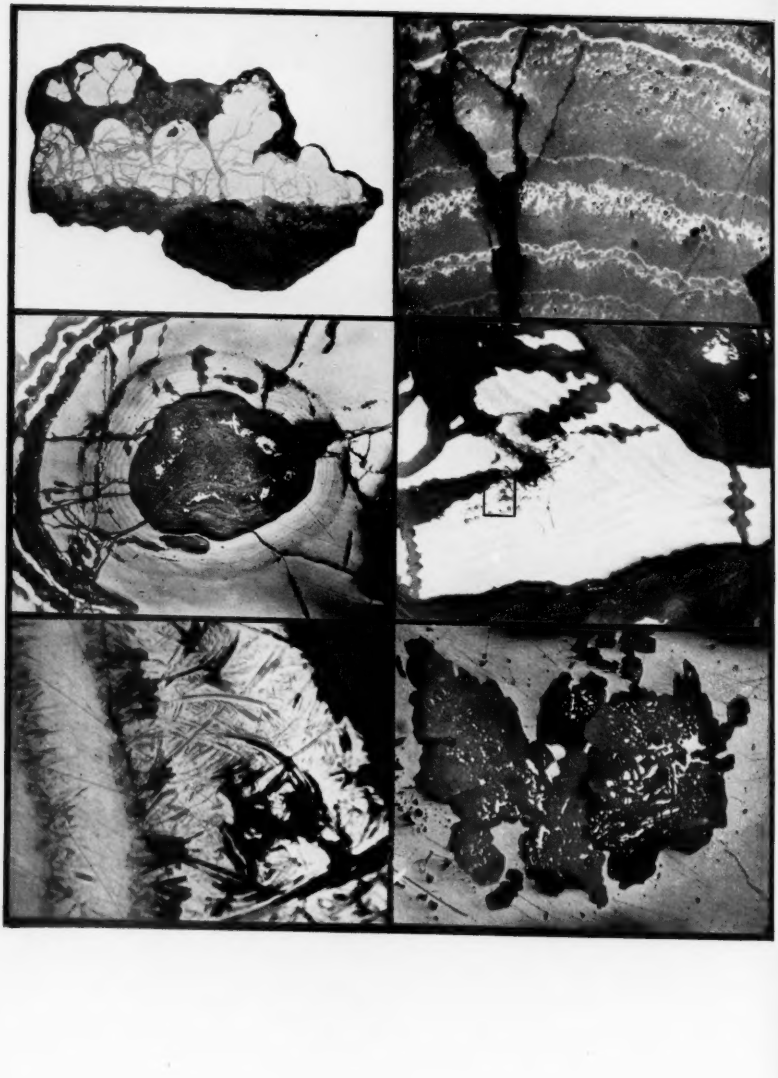


FIG. 3. Chalcopyrite (white) with covellite (gray and black) cutting sphalerite (gray). × 120.

FIG. 4. Galena (white) replacing sphalerite (gray). × 120.

FIGS. 5 and 6. Metacolloidal intergrowths of sphalerite and galena. Sphalerite (gray), galena (white) and gangue (dark gray). × 82. (Oil immersion.)

FIGS. 7 and 8. Graphic intergrowth of chalcopyrite and mineral X (mottled gray) with needles of covellite (black) developing along the grid structure. The intergrowth, resembling fine-grained wood, is not clearly resolved. × 410. (Oil immersion.)



17

19

21

generally averaging from one half to one millimeter in cross section but in the very massive chalcocite, grains several times coarser than this are common. Blue and white chalcocite are intermingled. A single grain may be composed largely of one or the other variety but more commonly the two are mixed with little regard for grain boundaries. In places the blue chalcocite is cut by cigar-shaped blades of white chalcocite, suggesting a coarse but poorly developed lamellar structure. When etched these grains all show orthorhombic cleavage.

The replacement of calcite by chalcocite (Fig. 22) is hardly to be expected under conditions of supergene mineralization,[20] and it is of interest to inquire what other evidence can be found to suggest a hypogene origin for the chalcocite. Kelley[21] lists "large grain size" and "lamellar rhombic chalcocite" among other factors as indicating isometric ancestry of rhombic chalcocite. Further, many of the grains of chalcocite exhibit cracks parallel to the basal cleavage. These cracks may be open or filled with malachite. That they are not replacement veinlets is shown

FIG. 17. Botryoidal masses of bornite. (About 4/5 natural size.)

FIG. 18. Concentric bands of chalcopyrite (white) in botryoidal bornite (gray). ×42.

FIG. 19. Metacolloidal intergrowth of chalcopyrite and luzonite with colloform structure, partially replaced by "copper pitch." "Copper pitch" (dark gray), chalcopyrite (light gray) and luzonite (bands in chalcopyrite and light gray areas in the center of the colloform structure). ×24.

FIG. 20. Metacolloidal intergrowth of chalcopyrite and luzonite. Chalcopyrite (white) with bands (light gray) of luzonite intergrown with chalcopyrite. Note the selective replacement of the chalcopyrite-luzonite bands by "copper pitch" (dark gray). Fig. 21 is an enlargement of the area outlined in ink. ×54.

FIG. 21. Intergrowth of chalcopyrite (white) and luzonite (gray) with "copper pitch" (black) selectively replacing the luzonite. ×335. (Oil immersion.)

FIG. 22. Chalcocite (light gray) replacing calcite (dark gray). ×60.

[20] Bateman, A. M.: Primary chalcocite. Bristol copper mine, Connecticut. ECON. GEOL., vol. 18, p. 149, 1923.

[21] Kelley, V. C.: Paragenesis of the Colorado copped sulphides, Cananea, Mexico. ECON. GEOL., vol. 30, pp. 670–671, 1935.

by their regularity and the fact that they invariably pinch toward grain boundaries. Hsieh describes and beautifully illustrates the same phenomenon in coarse grained rhombic chalcocite and concludes that this material is "a result of hypogenic alteration" of bornite which "has been almost entirely changed to chalcocite."[22] This, however, does not explain the presence of these cracks. Dolmage[23] describes shrinkage cracks in rhombic chalcocite and concludes that they developed at the time of inversion from the isometric to the orthorhombic form due to contraction. He failed to make clear the orientation of these cracks with respect to the crystal structure but states:

> Almost all of the larger areas have peculiar cracks crossing them, which fade towards the margins and become wider at the center. None of them were seen to cross from one area of chalcocite to another and all were of this peculiar shape. The size of the cracks varies directly with the size of the grains in which they occur, those in the largest grains can easily be seen with a hand lens. They strongly suggest shrinkage cracks and are of constant occurrence. Some of them are filled with calcite or other gangue minerals, while many of them are empty.[24]

Stephens shows, however, that "the inversion of chalcocite from the orthorhombic to the isometric system is accompanied by a decrease in volume of about 2.6 per cent. . . .,"[25] exactly the reverse volume change postulated by Dolmage. Thus, it appears that this criterion cannot be used to suggest isometric ancestry of rhombic chalcocite, but the problem still remains to explain the presence of these cracks that certainly resemble shrinkage structures.

"Copper Pitch," Iron Oxide, Malachite, Chrysocolla and Azurite.—The complex nature of "copper pitch" has been emphasized by Schwartz[26] and by Guild.[27] The term "copper

[22] Hsieh, C. Y.: Geological and microscopical study of some copper deposits of China. Geol. Soc. China, Bull. 8, p. 293, 1929.

[23] Dolmage, V.: The copper silver veins of the Telkwa district, British Columbia. ECON. GEOL., vol. 13, pp. 364 and 371, 1918.

[24] Idem, p. 364.

[25] Stephens, M. M.: The identification of types of chalcocite by use of the carbon arc. ECON. GEOL., vol. 30, p. 617, 1935.

[26] Schwartz, G. M.: Paragenesis of the oxidized ores of copper. ECON. GEOL., vol. 29, pp. 55–75, 1934.

[27] Guild, F. N.: Copper pitch ore. Am. Mineralogist, vol. 14, pp. 313–318, 1929.

pitch" implies a substance which in polished sections has a brownish-gray color, hardness about D, is opaque or semi-opaque and possesses marked anisotropism. This material is essentially melaconite, but it is generally so closely associated with non-opaque minerals, especially malachite, and with earthy and finely crystalline iron oxides, that these materials cannot be separated by definite boundary lines.

The primary ore from the upper level has been largely replaced by "copper pitch." Iron oxide is abundant in this material, occurring in finely crystalline veinlets and concentric bands and as earthy disseminations. Where the latter is present the "copper pitch" has a brownish or reddish color and internal reflection. In places the "copper pitch" exhibits a greenish internal reflection denoting the presence of malachite. Small botryoidal masses of malachite, azurite and chrysocolla occur in cavities, and veinlets of malachite cut the "copper pitch."

Malachite with minor amounts of "copper pitch" cut and replace to some extent the chalcocite from the lower level.

COPPER RIVET MINE.

The Copper Rivet mine is located on the west wall of Salt Wash canyon at a point 4½ miles from the Dolores River. Here the canyon opens abruptly into the steep-walled and flat-floored basin of Sinbad Valley. The mine lies about 300 feet above the bed of Salt Wash.

As in the mines described above, mineralization has occurred along a fault zone, the ore developing best in the lower part of the Wingate sandstone. The plane of the fault strikes N. 40° E. and dips nearly vertical. Displacement is estimated to be about a hundred feet, the beds on the southeast side being downthrown.

Mineralization is lean. The primary ore, consisting principally of chalcopyrite and luzonite, has been largely oxidized. Small masses of chalcocite, exhibiting a "crackled porcelain" structure on etching and carrying minute disseminated grains of chalcopyrite and bornite, were observed in a few sections. The gangue is principally calcite.

MINERALIZATION IN SALT VALLEY, UTAH.

Butler [28] has discussed briefly the copper-silver mineralization of Salt Valley, Utah. This valley, cut in the crest of a salt anticline, extends southeastward from a point several miles south of Thompsons to the Colorado River. The following statements are quoted from Butler's description, with the exceptions of the remarks enclosed in parentheses, which are added by the present writer:

> The formations along it (Salt Valley) were not carefully traced into areas where they are known, but it is thought that the copper-bearing beds are in the McElmo (Morrison) formation. . . . Toward the north, where the prospects were visited, there has been considerable fissuring parallel with the anticline and in some places there has been movement along the fissures, though the displacement has probably not been great.
>
> The copper deposits occur on both sides of the valley, from about 10 miles southeast of Thompsons nearly to Grand (Colorado) River, in the portions of the anticline nearest the crest. . . . The ore deposits are in the vicinity of fissure zones, but the ores do not generally occur in the fissures, usually impregnating the sandstone. Near the old Indian trail a small stringer of ore apparently occurs in a fissure. . . .
>
> Some of the copper ores, notably those from the fissure near the old Indian trail, are said to contain considerable silver. This ore contains barite as a gangue mineral, and the presence of rather abundant remnants of chalcopyrite indicates that that mineral was the most important original copper sulphide. . . .

Hoosier Mine.

In the summer of 1933 the present writer made a hasty visit to the Hoosier mine which at that time was being operated by Mr. Alex Ringhoffer. This mine lies along the southwest wall of Salt Valley at a point about 10 miles south of Thompsons (Fig. 1). The mine is located at the intersection of two faults. One trends N. 35° W., essentially parallel to the strike of the Salt Valley anticline, and the other strikes N. 80° E. Displacement along both faults is small but could not be determined at this point. Considerable fracturing accompanies the faults, especially at their intersections.

[28] Butler, B. S.: Ore deposits of Utah. U. S. Geol. Surv. Prof. Paper 111, pp. 615–616, 1920.

The rocks at the surface in the vicinity of the mine are thought to belong to the Morrison formation. They consist of massive white sandstone beds or lenses with interbedded gray and red shale.

According to Mr. Ringhoffer silver is the principal value of the mine, with less copper and a little gold. Silver occurs principally as the chloride disseminated in the vein filling and adjacent sandstone. Small amounts of native copper and silver and a little ruby silver have been found by the owner. Barite with some calcite form the gangue.

The following minerals have been identified in polished sections: Chalcopyrite, the chalcopyrite-X intergrowth, luzonite, tennantite (?), chalcocite, covellite, pyrite, the oxidized copper minerals, iron oxide and hausmannite (?).

Chalcopyrite, the chalcopyrite-X intergrowth, luzonite and tennantite (?) generally occur in small isolated grains surrounded by the oxidized minerals in the gangue. In places the chalcopyrite-X intergrowth replaces the pure chalcopyrite. This intergrowth is identical with the chalcopyrite-X intergrowth in the Cashin ore. As a rule it is more or less replaced by covellite but in places in this ore chalcocite, without covellite, but developing in the same manner replaces the intergrowth.

Pyrite occurs as irregular veins or masses in the sandstone. It is cut and replaced by hausmannite (?) and the whole is embedded in coarse grained rhombic chalcocite. The latter veins the hausmannite (?) but it is rarely found in direct contact with the pyrite.

ORIGIN OF THE DEPOSITS.

The problem of genesis of these deposits concerns itself not so much with the type of the mineralizing solutions but with the nature of them. There can be little doubt that these deposits are hydrothermal in origin, though the writer is at a loss to know exactly how to classify them. The veins themselves are typical of thermal mineralization of the lower temperature class. It is believed that the intimate mineral associations, replacements and

intergrowths could not possibly have developed from meteoric solutions. In addition, evidence was offered which, though not conclusive, strongly suggests that much of the chalcocite is primary or hypogene.

Sulphide Enrichment and Oxidation.

With the exception of the ore from the lower level of the Sunrise mine and the bornite-chalcocite specimens from the Cashin mine, chalcocite is a relatively rare mineral. Where oxidation is abundant, narrow rims of chalcocite commonly border grains of chalcopyrite and bornite and small isolated masses of chalcocite occur in the oxidized material. Chalcocite of this nature is typically supergene, and although it at one time may have been more abundant and subsequently has become oxidized, this possibility in this case is not impressive. In western Colorado the stratigraphic range of the ores along the faults is surprisingly limited, suggesting that the ore-bearing solutions "dumped" their load of metals at the first favorable horizon, being in this case the massive Wingate sandstone. There is little evidence of much mineralization above this horizon, hence there is little material available for enrichment. Further, pyrite is conspicuously rare in these ores, whereas it is generally abundant where secondary copper concentration is important. Also impressive is the abundance of carbonate, both as a gangue mineral and as the cement in the adjacent sandstone. Butler [29] suggests that sulphide enrichment is generally absent in the presence of carbonates.

The abundant covellite in the Cashin ore presents peculiar difficulties. This problem would probably be less disturbing if the ore could have been studied in the mine. The fine grained blades and aggregates of covellite that occur sparsely disseminated through and develop along the contacts of the other ore minerals would undoubtedly be considered supergene under ordinary conditions. They may or may not be in this case. But by far the

[29] Butler, B. S.: Geology and ore deposits of the San Francisco and adjacent districts, Utah. U. S. Geol. Surv. Prof. Paper 80, pp. 141 and 142, 1913.

greater amount of the covellite in this deposit is believed to be hypogene. (1) This covellite occurs entirely without chalcocite. (2) In the sandstone replacement ore, the covellite is distributed throughout the chalcopyrite, showing no relationships to grain boundaries, mineral contacts or fractures. Such replacements are more typical of hypogene mineralization or enrichment. (3) In places covellite is intergrown with luzonite, possibly in colloform structures. (4) Veins and irregular masses of covellite are in places bordered by a narrow zone of chalcopyrite and luzonite. (5) Botryoidal masses of luzonite developed on large masses of coarse grained covellite have been observed. If luzonite is hypogene then this covellite must be also.

The primary ores from the Sunrise, Copper Rivet and Hoosier mines have been highly oxidized. On the other hand, in none of the 50 polished sections of Cashin ore studied were any oxidized or clearly secondary minerals observed, with the possible exception of a few small and scattered grains of chalcocite noted in several sections. The lack of oxidation is easily explained. Development at the Cashin mine is greater than at the other deposits. Today a large part of the mine is flooded, and it appears that much of the ore mined lay beneath the normal water table. In addition, the cutting of the La Sal Creek canyon has probably been accomplished quite recently. It is thought that the absence of oxidized and clearly secondary minerals is an important argument for hypogene mineralization in this case.

Nature of the Mineralizing Solutions.

This problem cannot be satisfactorily handled with the information available. It presents, however, immensely interesting possibilities. The solutions were probably in part typical hydrothermal solutions but colloids undoubtedly played a rôle of great importance. Metacolloidal minerals are abundant and colloform structures and intergrowths are generally well developed. To the latter group belong the sphalerite-galena, chalcopyrite-luzonite

and chalcopyrite-bornite intergrowths. Possibly to this group may be added the covellite-luzonite intergrowths.

Lasky [30] has postulated a colloidal origin for some of the ore minerals from the Kennecott mine and has given an excellent review of the literature concerning this type of mineralization. Readers interested in this problem are referred to this paper. Many features of similarity between the Kennecott ore and the ores just described are obvious, but it hardly seems advisable to stress this point at present.

SUMMARY AND CONCLUSIONS.

The copper-silver vein deposits in the eastern Colorado Plateau Province are not related to the "Red Beds" type of copper mineralization. The five mines visited by the author are definitely related and others in the region appear to be of similar nature. These deposits are all of the fissure vein type and occur along high angle faults of small displacement. The best ore develops where these faults cut massive sandstone beds. A few bodies of late Mesozoic or post-Mesozoic igneous rocks are known to occur in this general region but show no close relationship to the ore deposits.

The ore consists principally of sulphides of copper, with dolomite, calcite and barite as the gangue minerals. The ore minerals and the gangue generally fill fissures and cement a fault breccia but in places the metallic minerals replace the sandstone.

These deposits are thought to be of hydrothermal origin, with colloids playing an important rôle in the formation of the ores. Supergene enrichment is not important. Oxidation is negligible in the Cashin and Cliffdweller mines but abundant in the Sunrise, Copper Rivet and Hoosier mines.

ACKNOWLEDGMENTS.

This study was undertaken in connection with general studies of the "Red Beds" ore deposits. Field and laboratory work have

[30] Lasky, S. G.: A colloidal origin of some of the Kennecott ore minerals. ECON. GEOL., vol. 25, pp. 737–757, 1930.

been supervised and financed by the Department of Geology of Princeton University, for which aid the writer is greatly indebted. Thanks are due to many members of the faculty of the Department of Geology, especially Professor Edward Sampson who visited the Cashin and Cliffdweller mines with the writer in 1934 and who has given unlimited aid and encouragement during the preparation of this paper, and to Professor A. F. Buddington for careful reading of the manuscript.

PRINCETON UNIVERSITY,
PRINCETON, N. J.,
March 23, 1936.

HYPOGENE ANHYDRITE FROM McINTYRE MINE, PORCUPINE DISTRICT, ONTARIO.

G. B. LANGFORD and E. G. HANCOX.

INTRODUCTION.

In the epithermal stages of ore deposition the prevalence of calcite and dolomite is evidence of the abundance of calcium ions, and commonly there is a sufficient quantity of sulphate ions to bring about deposition of barite. The instances on record, however, in which such an ionic condition has been expressed by deposition of anhydrous calcium sulphate, or anhydrite, are remarkably few. It is possible that the presence of small amounts of hypogene anhydrite or gypsum in various deposits wherein it might have been expected has escaped attention or has been attributed to supergene agencies.

Rogers [1] has listed about sixty occurrences of anhydrite in the United States, many of them not vein deposits. More recently Butler [2] has discussed the significance of sulphate minerals in ore deposition, with special reference to calcium sulphate. The more important of the occurrences noted by these authors are reviewed later in this paper. Since anhydrite has only exceptionally been attributed to a magmatic source, the discovery of a new occurrence of undoubted hypogene origin, associated with certain of the gold-bearing quartz-carbonate veins of the Porcupine district in Ontario, is noteworthy.

In explanation of the rarity of hypogene anhydrite it is concluded that two conditions are separately necessary for its formation, namely a high relative concentration of sulphate ions in the ascending solutions and an abundance of available calcium in

[1] Rogers, A. F.: Notes on the Occurrence of Anhydrite in the United States. Sch. of Mines Quart. (Columbia Univ.) vol. 35, no. 2, p. 123, 1915.

[2] Butler, B. S.: Primary (Hypogene) Sulphate Minerals in Ore Deposits. Econ. Geol., vol. 14, p. 581 et seq., 1919.

the rocks closely adjacent to the point of deposition. The temperature of the last magmatic solutions to leave any effect, as deduced from evidence in the McIntyre mine at Porcupine, appears to have been between 66° and 30° C.

The tapping of a water pocket in the McIntyre mine is noted, the composition of which is unusual in that it has a high sodium chloride content together with an excess of free sulphate radicle. Its significance is not clear, although it does not appear to be a normal type of either vadose or connate water.

OCCURRENCE.

The material upon which this paper is based came from the McIntyre mine, which is located in the Pearl Lake section of the Porcupine gold area in Ontario. The country rock is a series of Keewatin volcanics that has been highly folded and altered. Following the folding, intrusions of alaskite porphyry, of Algoman age, took place. These, and later the veins, were controlled by fold structures in the Keewatin so that the veins are generally associated with porphyries, although the association is physical and not chemical. A series of albitite dikes was intruded later than the porphyries but earlier than the veins and is probably comagmatic with the latter.

In the neighborhood of Pearl Lake the most important intrusive is the "Pearl Lake porphyry," an irregular mass lenticular in plan, and with an easterly pitch. At the surface its greatest length, striking E.N.E., is about 5,000 feet. From the 1,500 level downwards its western end develops a reentrant, which gives to this end the form of an inclined inverted trough. Mineralized veins occur in well-defined fractures that have a general strike of N. 65° E. and form an aureole around the Pearl Lake porphyry. They are strongest in the Keewatin lavas; in the porphyry they rarely carry gold.

The mineral sequence is divided into three stages:

1. Early quartz and tourmaline veins, with or without pyrite. These are non-auriferous.

2. Early veins re-opened and a second phase of quartz with

ankerite, albite, scheelite, chlorite, sericite, auriferous pyrite, free gold, sphalerite, galena, chalcopyrite, and tellurides. These are not given in order of deposition.

3. Late quartz and calcite veins with or without pyrite. These are non-auriferous.

These three stages are all part of one period of mineralization which was interrupted by several structural readjustments.[3] Graton[4] pointed out the existence of two approximately concentric zones, the inner gold-bearing, in which quartz-ankerite veins predominate, and the outer unproductive, the veins being quartz-calcite.

Anhydrite is found in veins that occur within the inverted porphyry trough mentioned above, and that lie within the quartz-ankerite zone. Similar material has been noted in the adjacent Hollinger mine. Within this trough, sulphates have been found from 2,000 to the 2,500 levels and from the 3,750 to the 4,925 levels. The area between the 2,500 and 3,750 levels has not yet been opened up by mining operations. In the upper levels the sulphate takes the form of selenite, filling small vugs that are lined with quartz crystals. Such vugs occur at random in the veins, but are not common, and are confined to the inverted trough zone beneath the porphyry. In the lower levels anhydrite is present in discontinuous lenses with a maximum width of three inches and a length of up to six feet. These veinlets occur in both Keewatin lava and Algoman porphyry, and have been found in the latter as far as 700 feet from the contact. In general, the anhydrite may be intergrown with quartz and carbonate, and does not appear to be the filling of either vugs or later veinlets cutting the quartz-carbonate veins. Examination of freshly-mined surfaces suggests that anhydrite is a vein mineral later than both quartz and ankerite.

The lowest horizon at which oxidizing surface waters have been met in the mine is the 1,500 level. Since the region has

[3] Hurst, M. E.: Vein Formation at Porcupine, Ontario. ECON. GEOL., vol. 30, p. 108, 1935.

[4] Graton, L. C., McKinstry, H. E., and others: Outstanding Features of Hollinger Geology. Can. Min. Met. Bull., No. 249, p. 11, 1933.

undergone long-continued erosion and heavy glaciation it is reasonable to suppose that this horizon represents the deepest level at which supergene processes can have been effective. The presence of anhydrite nearly 3,500 feet below this horizon, in vein-zones too tight for water-circulation, taken in conjunction with its intimate association with minerals indisputably of hypogene origin, leaves little doubt that in this occurrence it is a late member of the period of mineralization that gave rise to the auriferous veins.

A number of thin sections of anhydrite-bearing gangue were examined, the country-rock of which was either lava or porphyry. The above-stated conclusion was confirmed and the paragenesis of anhydrite determined. Tourmaline, albite, quartz, anhydrite, ankerite, pyrite, and probably scheelite (smallness of grain-size prevented absolute optical diagnosis) were recognized. The early quartz associated with either tourmaline or albite could not be distinguished from granular quartz intergrown with ankerite; the latter two were, to all appearances, of the same generation. In every case where ankerite and anhydrite are in juxtaposition, considerable embayment of ankerite was visible and "islands" of ankerite, evidently continuous with the "mainland," surrounded by anhydrite, are common. This leaves little doubt that anhydrite formed, at least in part, by replacement of ankerite. In one case, quartz clearly replaced anhydrite and in others it is more than probable that the two were deposited concurrently. The period of formation of anhydrite, therefore, was subsequent to that of ankerite but was spanned by that of quartz. This is in agreement with the findings of Hurst,[5] that quartz was a late-forming mineral. Since no late-stage calcite was recognised, it is impossible to tell what relation anhydrite bears to it. Owing to the euhedral character of the pyrite observed in the sections it is a matter of surmise whether it persisted during the replacement of ankerite, being stable in the presence of later solutions, or continued forming at the time of replacement. A mineral resembling scheelite was noticed in two of the sections examined, of the

[5] Hurst, M. E.: *Op. cit.*, p. 122.

same generation as anhydrite, although its identification is not conclusive.

THE FINAL STAGES OF MINERALIZATION.

The localization of calcium sulphate to a zone closely coincident with the axis of the inverted trough of the western end of the Pearl Lake porphyry seems significant. From its occurrence over such a limited extent the inference may tentatively be drawn that conditions slightly abnormal to the region were extant. On the other hand it is not impossible that anhydrite may be very sporadically distributed throughout the region. In a late phase of mineralization, possibly subsequently to final deposition of carbonate, though this is not proved, ascending sulphate-bearing waters found themselves confined below the inclined western end of the porphyry. As they rose along the trough until temperature conditions were favorable they interacted with carbonates previously deposited, causing replacement by anhydrite in minor fractures of the same stage of fissuring, such as Hurst's "ladder structures."[6] Some replacement by quartz also took place.

Somewhere between the (present) 3,750 and 2,375 levels of the porphyry the latest conditions of mineralization caused the formation of selenite in place of anhydrite. It has previously been demonstrated that a supergene origin for this selenite is unlikely. In the absence of conclusive underground evidence two possibilities are presented. Either anhydrite in and above this unexplored ground originally occupied vugs which now contain only selenite, and, in a final wave of solutions at a temperature lower than its inversion point, was transformed into selenite, or else, in a single stage of deposition, somewhere in this ground the temperature had fallen sufficiently to inhibit crystallization of anhydrite. Further underground development would serve to distinguish between these alternatives.

The work of van't Hoff established that the inversion point between anhydrite and gypsum, in water containing only calcium sulphate, is 66° C. Anhydrite forms above 66° C. and gypsum

[6] Hurst, M. E.: *Op. cit.*, p. 114.

below 66° C. The presence of other salts in solution depresses the inversion point; in a solution of sodium chloride it might be as low as 30° C. Although the earliest deposition of anhydrite, therefore, may have occurred at some temperature considerably in excess of this range (30°–66° C.), whichever of the two possible sequences for the end-stage of mineralization postulated above is correct, that end-stage must have produced a temperature below the range of 30°–66° C. On the one hand, the final wave of solutions could not exceed it; on the other, somewhere in the unexplored ground, the single phase of sulphate waters fell to a temperature below it. Although no attempt has been made to determine the temperature of formation of the main period of mineralization in the Porcupine district, the evidence obtained within the McIntyre mine would appear to suggest that the final phase did not exceed 30°–66° C. in temperature.

The appended equation represents the reversible reaction involved in replacement of calcite (similarly ankerite) by anhydrite. For convenience the base accompanying the sulphate ion is designated as sodium, though this is not essential.

$$CaCO_3 + Na_2SO_4 \rightleftharpoons CaSO_4 + Na_2CO_3.$$

In terms of the law of mass action this can be stated as

$$\frac{[CaCO_3] \times [Na_2SO_4]}{[CaSO_4] \times [Na_2CO_3]} = \text{a constant.}$$

Since there is always an excess of calcium carbonate and since in equilibrium there will be a constant amount of reactive calcium sulphate available, the factors $[CaCO_3]$ and $[CaSO_4]$ may be assumed to remain constant. The condition for equilibrium (at a given temperature) is, therefore, that the ratio of sulphate and carbonate concentrations shall remain constant. Furthermore, since anhydrite has a far higher solubility than calcite, it follows that this ratio is high; in other words, that to attain a situation in which calcium sulphate is being precipitated requires a high relative concentration of sulphate ions in the solution. In the

case of barium, on the other hand, barite being less soluble than witherite (barium carbonate), the ratio is low and commonly the required concentration of sulphate is exceeded, so that barite is precipitated where anhydrite is not. The lack of a sufficient concentration of sulphate ions is cause enough for the rarity of anhydrite in ore deposits associated with limestones or other abundant calciferous material, despite the presence of barite.

Butler,[7] quoting experimental data obtained by Melcher, has pointed out that owing to the decreasing solubility of anhydrite with rising temperature, a mineralizing solution saturated with calcium sulphate at depth at moderate or high temperature would not, upon ascent and cooling, deposit this load. In the case of the Porcupine anhydrite it is not necessary to assume that calcium sulphate, as such, has travelled in solution. Ascending sulphate-bearing solutions would extract calcium from pre-existing minerals (ankerite) at or near the present location of anhydrite veinlets. Exactly the opposite conclusion would hold for barite, however, because barium sulphate, increasing its slight solubility with rising temperature, is potentially a far traveller. It appears necessary, therefore, to postulate a source of calcium that is local relative to the point of deposition of anhydrite. A survey of the American literature dealing with mines in which anhydrite has been observed was undertaken, and in every case where sufficient detail was available this hypothesis was substantiated. The more important localities will now be considered briefly.

Brown [8] has recently recognised post-sulphide anhydrite, associated with abundant barite, in the Balmat, New York, zinc mine. As in the McIntyre mine, the sulphates replace carbonate. The country-rock is a limestone, so that in all phases of mineralization, calcium ions must have been present to the saturation point; yet it is to be noted especially that barite far exceeds anhydrite in bulk, a circumstance to be expected from the foregoing theoretical

[7] Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah. U. S. Geol. Surv. Prof. Paper 80, p. 123, 1913.

[8] Brown, J. S.: Structure and Primary Mineralization of the Zinc Mine at Balmat, New York. Econ. Geol., vol. 31, p. 252, 1936.

discussion. Discussing the origin of barite and anhydrite in the Cactus mine, Utah, Butler [9] rejects his earlier postulate that ascending sulphate waters reacted with descending solutions carrying calcium carbonate and asserts that a sufficient amount of calcium to account for the anhydrite would be available from the alteration of monzonite in the fissure walls, from which it is known that calcium has been removed. In the White Oaks district of New Mexico [10] a similar leaching of plagioclase in the monzonite wall-rock has taken place, and gypsum, probably an alteration product of anhydrite, is found in the gangue. Lindgren and Bastin [11] state that a late stage of mineralization in the Braden copper deposit of Chile was characterized by leaching of brecciated intrusives and by the minerals calcite (amongst other carbonates), anhydrite, and barite. Furthermore, in the final stage, with a further lowering of temperature, anhydrite gave place to gypsum. Boyle [12] regards the anhydrite of the Bully Hill district of California as being derived from the limestones through which the solutions passed. In the Britannia mines of British Columbia [13] zonal deposition of sphalerite-pyrite-chalcopyrite ores with respect to a Mesozoic batholith has been described. In the outer zone and during a late low temperature phase of mineralization, subsequent to sulphide formation, abundant anhydrite was deposited, largely by replacement of silicified porphyry. The more advanced stages of wall-rock alteration, preceding the sulphate phase, were marked by complete silicification of feldspars and the removal of earlier calcite. That the leaching of the country-rock was sufficient, in bulk, to supply the large amount of calcium required to account for the massive veins

[9] Butler, B. S.: *Op. cit.*, p. 597.

[10] Lindgren, W., etc.: Ore Deposits of New Mexico. U. S. Geol. Surv. Prof. Paper 68, p. 180, 1910.

[11] Lindgren, W., and Bastin, E. S.: The Braden Copper Deposit, Rancagua, Chile. Copper Resources of the World, 16th Internat. Geol. Congr., vol. 2, p. 468, 1935.

[12] Boyle, A. C.: Geology and Ore Deposits of the Bully Hill Mining District, California. Am. Inst. Min. Met. Eng. Trans., vol. 48, p. 113, 1915.

[13] James, H. T.: Britannia Beach Map-area, British Columbia. Can. Geol. Surv. Mem. 158, p. 123.

of anhydrite, during the final cooling period of the solutions, is not indicated, but again in this occurrence there is circumstantial evidence that late magmatic sulphate solutions could react with calcium derived locally.

In the McIntyre occurrence the degree of sulphatization of earlier gangue, evident at the present time, is very slight, and, relative to the total area affected by mineralization, is very local. It is apparent, therefore, that conditions favoring sulphate formation within the range of the ascending solutions were only exceptionally attained. There is no direct evidence in support of Butler's [14] interpretation of these conditions, that at lower temperatures they are favorable to reduction of ferric compounds and oxidation of the sulphur, but the abundance of ankerite and pyrite here indicates that ferrous iron was the stable form. The combination of sulphur with ferric oxides in the minerals of the wall-rock to form pyrite would furnish oxygen for the oxidation of the sulphur remaining in the magmatic emanations.

WATER POCKET.

During diamond drilling on the 4,175 level a considerable pocket of water was tapped, which emerged under pressure and drained for several days. The recalculated analysis showed that over fifty per cent. of the total solids consisted of sodium chloride. Other bases found were calcium and magnesium, and, contrary to expectation, only traces of silica, alumina, and ferric oxide were present. There was, furthermore, a decided excess of free sulphuric acid. Other small water pockets have been observed, but no analyses of their contents taken. It has been pointed out that ground water is lacking below the 1,500 level, for the rocks of the mine are non-porous and fracture-zones are too tight for water-circulation. The composition of this dilute solution is, in fact, unusual. At present its significance is not clear, since considerable difficulties are presented in ascribing to it either a vadose or connate (*i.e.* pre-Cambrian) origin, or a relationship with the mineralizing solutions.

[14] Butler, B. S.: *Op. cit.*, p. 602.

Two analyses are appended, one in terms of the percentage of solids, the other a recalculation in terms of chemical equivalents of acids and bases.

I. Percentage by Weight.

Chloride	0.25
Sulphate	0.20
Silica	0.001
Iron and aluminum oxide	0.001
Calcium oxide	0.093
Magnesium oxide	0.038
Sodium oxide	0.19
Total	0.773%

II. Recalculated to Chemical Equivalents and Expressed as Percentages of Total of Solids Present.

Strong acids.	SO_4	21.3	
	Cl	36.14	
Weak acid.	SiO_2	0.15	
Alkali.	Na	15.7	
Earths.	Ca	16.9	
	Mg	9.7	
Metal.	Fe	0.10	
Total		99.99	Excess of free acid: 15.14

McIntyre Mine, Schumacher, Ont.,
Laboratory of Economic Geology,
Yale University, New Haven, Conn.,
May 28, 1936.

THE OCCURRENCE OF MINUTE QUANTITIES OF MERCURY IN THE CHINLE SHALES AT LEES FERRY, ARIZONA.

CARL LAUSEN.

THE presence of small quantities of gold in the Chinle shales has been known for a number of years, and was described by Professor A. C. Lawson[1] in 1913. Apparently, at that time the presence of small amounts of mercury in these shales was unknown, for Lawson made no mention of this element in his published account.

For a number of years attempts were made to recover the gold from these rocks. Heavy machinery, including boilers, was hauled for many miles over wagon roads and installed on the north bank of the Colorado River at Lees Ferry. It seems that hydraulicking was the method most frequently used, as the shales were known to disintegrate and break down quite readily in a stream of water. The mushy liquid heavily laden with flocculent, colloidal matter, and carrying some sand grains in suspension, was permitted to flow over amalgamating plates. Burlap-covered tables lined with riffles were also tried. All these various efforts ended in failure, chiefly because the promoters failed to realize, either innocently or maliciously, the small amount of gold occurring in these shales and the very minute size of the particles.

The tests showed, however, that invariably more mercury was recovered than had been added originally in the various experiments. This fact led to the suspicion that the Chinle shales at this locality contained mercury. Since then the supposition has been confirmed by a number of assays.

Lees Ferry is located in Northern Arizona, within twelve miles of the Utah line, and approximately midway between the northeast and northwest corners of Arizona. This locality is the only place where the Colorado River can be crossed in a ferry[2] for a

[1] Lawson, A. C.: The gold of the Shinarump at Paria. ECON. GEOL., vol. 8, pp. 434–446, 1913.

[2] The old ferry has been abandoned since the completion of a steel bridge across Marble Canyon, a few miles downstream from Lees Ferry.

number of miles both up and downstream. Upstream from this locality are the cliffs of massive Navajo sandstone, and downstream are the nearly vertical walls of Marble Canyon. At Lees Ferry the sedimentary rocks have been sharply folded and the Echo Cliffs monocline brings the soft and easily eroded Chinle shales to the water's edge. Erosion in these soft shales has formed an easy approach to the river.

A few miles to the southwest of Lees Ferry are exposures of the Kaibab limestone, Permian, in which the Marble Canyon has been cut. The stripping back of the relatively soft, reddish sandstones and shales of the Moenkopi has developed a broad bench on each side of the Marble Canyon.

Gregory and Moore [3] give the following stratigraphic section of the formations in the region near the upper part of the Marble Gorge:

Jurassic:	
Navajo sandstone	1200 feet
Wingate sandstone	450 feet
Triassic:	
Chinle formation	850–980 feet
Shinarump conglomerate	0–115 feet
Moenkopi formation	390–540 feet
Permian:	
Kaibab limestone	517–600 feet
Coconino sandstone	0–93 feet
Hermit shale	530 feet

This paper is concerned only with the Chinle shales, consequently no detailed descriptions of the above formations are given here. The reader is referred to the publications on this interesting region for additional information.[4]

In the immediate vicinity of Lees Ferry the upper horizons of the Moenkopi formations consist predominantly of thinly laminated, sandy shales, chocolate-brown in color. Resting with ap-

[3] Gregory, H. E., and Moore, R. C.: The Kaiparowits Region. U. S. Geol. Surv., Prof. Paper 164, plate 5, 1931.

[4] Gregory, H. E.: Geology of the Navajo Country. U. S. Geol. Surv., Prof. Paper 93, 1917. Gregory, H. E., and Moore, R. C.: The Kaiparowits Region. U. S. Geol. Surv., Prof. Paper 164, 1931.

parent conformity on these thin shales are the massive beds of the Shinarump conglomerate. At Lees Ferry this formation consists mostly of white sandstone with pebbly layers.

The Chinle shales rest with apparent conformity on the Shinarump sandstone. The lower part of the Chinle formation is a rather drab gray, some layers with a decidedly greenish tone. The higher horizons are various shades of red, brown, green, and gray. At various horizons are thin beds of sandstone; they differ from the sandstones of the Shinarump chiefly in the grain size and the absence of pebbly layers. In the higher horizons these sandstones take on more of a reddish tone.

Above the Chinle are the red sandstones of the Wingate and Navajo formations. It is in these massive sandstones that Glen Canyon has been cut.

Gregory measured a section of the Chinle on the east side of the Paria River and found the following members:[5]

Chinle formation:	Feet
21. Sandstone, light red and buff	...
20. Shale and sandstone, light red, and gray	110
19. Shale, dark red	1
18. Sandstone, light red	2
17. Shale, buff	¾
16. Sandstone, green-white	1
15. Shale, red and gray	½
14. Limestone and limestone conglomerate, pink, green	22
13. Sandstone, "banded," white and brown	4
12. Shale and "marls," pink, lavender, and ash-gray	36
11. Limestone conglomerate, brown	1
10. Shale, red and green	6
9. Limestone conglomerate, brown	4
8. Shale, purple-green	6
7. Limestone conglomerate, brown	2
6. Shale and "marl" like No. 3	4
5. Sandstone, brown	1
4. Shale, brightly colored, yellow, green, lavender, purple, red, pink, gray, blue, and white	56
3. Sandstone, dull gray-brown	...
2. Shale, pink, purple, blue-green, red	10
1. Shale, gray	8
	298

[5] Gregory, H. E., and Moore, R. C.: Idem, p. 164.

From the above section, it may be seen that reddish sandstones with some shale predominate in the upper part of the formation, whereas limestone conglomerates are conspicuous members in the middle of the section. In the lower portion, shaly rocks prevail. The massive sandstones of members 21, and the reddish sandstones and shales of member 20 may well be a part of the Wingate formation. At this locality it is difficult to draw a dividing line between the Wingate and Chinle.

The samples assayed and listed in this paper all come from horizons 1 to 4 of Gregory's section. Samples Lees Ferry 1 to 5, inclusive, and samples Paria River 1 and 2 come from horizons 1 and 2 of the above section; and samples Paria River 3 and 4 from horizon 4.

One of the most striking features of the Chinle formation is the pronounced color banding. In the southern part of the Navajo Reservation, north of Holbrook, where the bedding is nearly horizontal, the strong bands of color can be traced by the eye for miles across the landscape, and with no apparent diminution in thickness. Undoubtedly, the difference in coloring is due largely to the abundance and degree of oxidation of the iron compounds in the shales. The uniformity of the banding over long distances suggests that the iron was an original constituent of the clays at the time of deposition, rather than a later introduction after consolidation.

The weathered surface of the Chinle shales forms a rather uniform, gentle slope, particularly where the harder beds of sandstone or marl are absent. The surface consists of a thin, slightly hardened crust beneath which are several inches of rather porous, crumbly, disintegrated shale. Such a slope of crumbly shale is difficult to climb when dry, and impossible when wet. Beneath the crumbly layer the Chinle shale is somewhat more consolidated and here takes on the characteristics of a dried clay, breaking into angular fragments of various sizes and shapes. During a heavy rainstorm the water running off of such a disintegrated surface is a thick fluid heavily charged with colloidal particles.

In the various attempts which have been made to extract both gold and quicksilver from the Chinle shales, advantage is taken

of the property these shales possess of swelling and disintegrating readily in water. It is interesting to watch a fragment immersed in a beaker of water swell to nearly twice its original size and then slowly disintegrate.

The mining of these shales is rather simple—a stream of water is played against a face of an open cut and the sludge run over appropriate machines for the extraction of both gold and quicksilver. As a matter of fact, it was in this way that the presence of mercury was discovered, for at the end of a test run the quantity of mercury recovered was invariably higher than the amount started with. None of the attempts to recover these two metals was successful, partly because the promoters of these various schemes failed to realize that the small quantities of the metals present could not be extracted profitably.

A large gold pan of the greenish shale was taken for washing from an open cut. In cutting the sample, care was taken to expose a fresh surface of the shale so as to be reasonably sure of no contamination. The sample was then panned in the Colorado River and a few small globules of mercury obtained.

Some of the samples taken for assay were carefully panned in the laboratory and the residue examined with the binocular microscope. In only two of the samples were minute globules noted of a silvery white color. These globules were too small to be separated, and tested chemically. As the assay returns show all the samples to contain mercury, a search was made for the various mercury minerals. Cinnabar can readily be recognized under the microscope by its bright red color, but none was seen. It is possible, therefore, that the mercury in part is present as some oxidized mineral, perhaps calomel.

The residue obtained on panning the different samples formed but a small part of the total sample. The sand is quite fine-grained, being less than one-tenth millimeter in diameter. The grains are both rounded and subangular. Quartz is the most abundant constituent, and is present as both clear and as translucent, milky grains. Some of the grains may be petrified wood. Next in abundance are irregularly shaped particles of hematite. Among the other minerals recognized were magnetite, tourmaline,

gypsum, barite, fluorite, muscovite, zircon, pyroxene and garnet. The garnet is of a light, pinkish color and is quite abundant in some samples. No feldspars were noted, and if originally present, have been thoroughly decomposed. Although gold is known to occur in all samples, no flakes or grains of this precious metal were seen.

In taking the samples, considerable care had to be exercised to avoid any possibility of error creeping in. Where samples were taken in open cuts, it was necessary to strip down the face to expose fresh surfaces. Where the samples were taken at the surface, all loose detritus was first removed. This precaution was taken because mercury has a measurable vapor pressure at ordinary temperatures, and, at the high temperature prevailing in this region during mid-summer, it is to be expected that much, if not all, the mercury occurring within a few inches of the surface will have been lost by evaporation. For that reason, it was necessary to take the samples at a depth of at least six inches. Usually the Chinle shale is quite firm at this depth, although traversed by numerous shrinkage cracks formed on drying.

Five samples were taken for assay at various horizons in the Chinle at Lees Ferry, and four samples were taken on the east side of Paria Creek, about two miles north of Lees Ferry. Three determinations were made on each sample for mercury, and the gold assays were run in duplicate. The analytical work was done by William A. Stone, Chief Chemist, Southwest Experiment Station, U. S. Bureau of Mines at Tucson, Arizona. The results of these assays are given below:

		Mercury.*	Gold. †
Lees Ferry	1.	0.0037	12.2
" "	2.	0.0020	8.0
" "	3.	0.0006	10.0
" "	4.	0.0018	6.0
" "	5.	0.0059	8.0
Paria River	1.	0.0058	6.0
" "	2.	0.0040	5.6
" "	3.	0.0078	8.0
" "	4.	0.0042	10.0

* Average of 3 determination expressed in per cent mercury.
† Value in cents per ton with gold at $20.67 per ounce.

It will be noted from the above assays that the amount of gold in the shales shows much less variation than does the quantity of mercury; and also, there is no apparent quantitative connection between the gold and mercury. For example, sample Lees Ferry No. 1 and Paria River No. 2 contain nearly the same amount of mercury, but one sample contains twice as much gold.

Of interest in connection with the occurrence of these two metals is their probable origin. The Chinle shales are clearly sedimentary in origin, and on the basis of vertebrate remains found, have been assigned to the Triassic. The presence of a species of *Unio* indicates a fresh water origin for these shales, and the sands and clays were deposited in a large lake or interior sea. At times, the water was quite shallow, for Gregory [6] reported the presence of mud cracks. Cross-bedding is a common feature of the sandstones and was formed by the rivers discharging sediments into the lake.

Only one chemical analysis of the shale is available. The abundance of colloidal material suggests a high alumina content. In their physical aspects the shales resemble bentonite, and it is possible much of the clay was derived from the decomposition of volcanic tuffs. The source of the igneous material, however, is unknown. In the immediate vicinity of known exposures of the Chinle formation, the volcanic activity postdates the Cretaceous.

At no place where samples were taken is there the slightest indication of hydrothermal action. Not only are there no veins or veinlets of quartz or calcite, but there is no evidence of silicification, bleaching or discoloration along fractures. Changes in color occur only in the different beds of shales and appear to be indigenous features of the shales.

In the absence of any indication of hydrothermal action, it is reasonable to assume that both the gold and mercury were transported by the streams that carried the particles of clay and sand. The deposit appears to be syngenetic in origin; however, a definite conclusion must await further examination and sampling of outcrops in other parts of the state, and in adjoining states.

[6] Gregory, H. E.: Geology of the Navajo Country. U. S. Geol. Surv. Prof. Paper 93, p. 46, 1917.

Exposures of Chinle shales extend southward from Lees Ferry to near Cameron, a distance of sixty miles. Throughout this distance, the outcrop forms a narrow band. From Cameron the trend is southeast, then east, with a progressive widening of the outcrop north of Holbrook. From here the trend is northeast, then north in the Chinle Valley, the type locality. Exposures of the Chinle formation extend northward into Utah for a distance of more than fifty miles, and eastward into New Mexico more than one hundred miles. The area underlain by rocks of this formation greatly exceeds ten thousand square miles. If only a small portion of Chinle shale carried minute amounts of mercury in the aggregate, the total quantity of mercury would be measured in the thousands of tons.

BILLINGS, MONTANA,
May 14, 1936.

GEOLOGY OF THE SILVER DEPOSIT AT COLQUIJIRCA, PERU.

H. E. MCKINSTRY.

DR. WALDEMAR LINDGREN [1] has recently published a paper on the Colquijirca Silver mine in the Andes of Central Peru. The present article is the result of five months of underground mapping and sampling in 1923–4 followed by laboratory studies at Harvard but has not been published previously. It is offered now in the hope that a first-hand description of the structure and field relations in this unusual ore deposit, which, as Lindgren points out, has been one of the most productive silver mines in the world, may be a useful supplement to his masterly laboratory investigation.

GENERAL GEOLOGY.

In this region, sediments ranging from pre-Paleozoic to early Tertiary are folded along northwesterly-trending axes and intruded by Tertiary acid stocks. In the immediate neighborhood the sequence is as follows:

Tertiary:	Marca-Punta Porphyry (intrusive) and Unish Tuff
Tertiary (?):	Calera Formation
	Shuco Limestone Conglomerate
	- - - - - Unconformity - - - - -
Comanchian:	(Sandstones and Limestones locally missing)
Liassic:	Paria Limestone
	- - - - - Unconformity - - - - -
Carboniferous (?):	Mitu Formation

Calera Formation.—The beds in which the ore occurs are clearly younger than the Paria Limestone and in fact are correlated on good evidence with formations younger than the

[1] Lindgren, W.: The Silver Mine of Colquijirca, Peru. ECON. GEOL., vol. 30, pp. 331–346, 1935.

Machay Limestone (Comanchian). They are believed by McLaughlin [2] to be probably Tertiary.[3]

The Calera formation consists of argillaceous limestone and interbedded shales. Much of it can be described as a gray sandy shale. The more massive beds are finely fragmental; the more fissile almost resemble a soft slate and are green to black. Limestone beds which are conspicuous on surface because of their superior resistance to erosion are found underground to be subordinate.

Marca-Punta Porphyry.—Two kilometers south of the workings is a plug of porphyry and tuff 3 kilometers in diameter. It is similar to many other plutonic rocks throughout the area which were intruded following the last (Incaic) period of folding which the Andes suffered (early Tertiary).[4] A microscopic study of the Marca-Punta porphyry was made by the late Dr. Roger D. Harvey whose description may be summarized as follows:

> The most conspicuous phenocrysts are orthoclases up to 10 cm. long. Smaller phenocrysts consist of basic andesine and rounded quartz. The ferromagnesians are biotite and subordinate hornblende. The holocrystalline groundmass consists of oligoclase, orthoclase, quartz and biotite. Accessories are: apatite, zircon, rutile, and magnetite. Alteration has reached an advanced stage and is marked by abundant secondary quartz and probably hydrothermal alunite. The ferromagnesians are altered to rutile and epidote. The feldspars are kaolinized.

This rock is very similar to the Cerro Monzonite porphyry which is held responsible for the mineralization at Cerro de Pasco.

Unish Tuff.—Adjoining the intrusive on the south is an area of tuff carrying some acid glass. Noble [5] believes that this is an extrusive phase of the porphyry which it resembles in composition

[2] McLaughlin, D. H.: Geology and Physiography of the Peruvian Cordillera, Departments of Junin and Lima. Geol. Soc. Amer. Bull. 35, p. 611, 1924.

[3] Ahlfeld, F.: Die Silbererzlaggerstätte Colquijirca, Peru. Zeit. Präkt. Geol. vol. 40, pp. 81–87, 1932, says of the ore-bearing beds: "Man rechnet sie dort der oberen Trias zu." This is at variance with the results of many years of detailed investigation carried out over a wide area by the Cerro de Pasco geological staff.

[4] Steinmann, G.: Geologie von Peru. Heidelberg, 1929. Reviewed by D. H. McLaughlin, ECON. GEOL., vol. 24, pp. 664–9, 1929.

[5] Noble, J. A.: Personal communication.

and that the tuff is younger than the Calera limestone. The tuff resembles certain fragmental rocks at Cerro de Pasco which there bear similar relations to a porphyry stock.

STRUCTURE.

The mine is on the east flank of a major anticline whose core exposes the Mitu formation. To the east and unconformably overlying the Mitu are found in succession, the Shuco and Calera formations. Still farther east the hills consist of Paria limestone. The fault that separates it from the Calera is concealed beneath an alluvium-filled valley but is clearly recognizable farther north toward Cerro de Pasco.[5a]

Most of the major faults in the Peruvian Andes are thrust planes along which anticlines have broken in the late stages of folding. This one is probably no exception. West of it the Calera beds are dragged into folds whose axial planes dip steeply eastward. Within the underground workings two complete synclines are exposed and the mineralization follows the bedding throughout the folds whose limbs have received local names as shown in Fig. 1.

The folds have a gentle southward pitch (15 degrees in the Principal syncline) and at the same time the anticline becomes more tightly compressed as it passes northward, developing a fault (with negligible displacement) that roughly parallels its axial plane. Within the country rock, slipping along bedding planes has developed gouge, but aside from such minor movements there is no faulting within the mine workings. There is, however, a zone of mild cross-folding [6] that distorts both limbs of the anticline. This fold, concave toward the east, produces a cross-trough in the east-dipping Principal limb and a gentle upward bulge in the corresponding portion of the west-dipping Mercedes limb. The influence of this cross-flexure will appear later.

[5a] McLaughlin, D. H., Bowditch, S. I., and others: The Cerro de Pasco District. Copper Resources of the World. Washington 1935, p. 519.

[6] The term "cross-folding" is here used without implication as to whether it accompanied or followed the main folding.

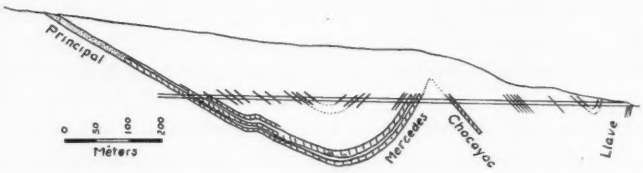


FIG. 1*A*. Cross-section along adit looking north. Gossan is shown by stippling. Sulphide mineralization by cross-hatching.

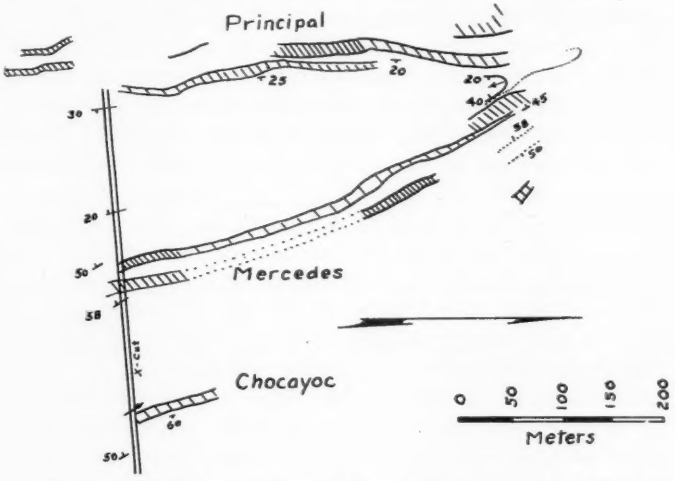


FIG. 1*B*. Plan of "Mantos" on Third Level. Mineralization is indicated by cross-hatching.

ORE DEPOSITS.

Mineralization is restricted, so far as known, to a single group of beds. Within this group the number of individual strata that have been replaced varies along both the dip and the strike, from a few centimeters of sulphides separated from the next ore-bed by several meters of barren rock, to a width of over ten meters so thoroughly mineralized as to be minable as a unit. The bedding

is so well preserved that it is rare to find a layer of ore a foot thick that does not show conspicuous traces of stratification; even in the thickest ore bodies there are generally beds of shale separating the ore into layers.

At the points of cross flexure (mentioned under "Structure") it is significant that the aggregate width of beds mineralized as well as the intensity of mineralization on both the Principal and Mercedes limbs is particularly great. Some 250 meters farther south there is another pair of oreshoots, one on each limb, and although the workings there were mainly inaccessible at the time of the examination, such mapping as could be done suggested similar structural relations. This localization of oreshoots may be due to gentle cross-fracturing accompanying the cross folding.

Nature of Replacement.—The replaced beds always carry some chert although the amount varies from individual layers a few centimeters thick either widely or closely spaced to five-meter thicknesses of nearly solid black cherty silica. Any particular bed may change along the strike or the dip from unsilicified rock to the highly silicified phase. Where chertification is extreme, the chief sulphide is always pyrite, which may be disseminated in chert or may occur in veinlets or lenses. Other sulphides, but particularly chalcopyrite are associated with the pyrite.

Contrasted in character to the chert-replaced beds are the galena-shale mantos with galena as the chief sulphide, nearly always accompanied by beautifully crystallized barite and only a little pyrite and chalcopyrite. The galena is generally not massive, but an aggregate of loosely attached crystals. Locally, small portions of certain beds have been dissolved out and galena crystals, attached to residual laminæ of the shale, extend into open spaces that also display clear and well-formed barite crystals. In a number of places the chert-pyrite type grades along the strike through the galena-shale type into lean beds, the succession suggesting local variation in the intensity of mineralization.

Although the generalization may be made that pyrite is most characteristic of the highly silicified beds, and galena of the kaolinized shale, all gradations and modifications may be found: kaolin

with disseminated pyrite, partly silicified shale with pyrite, beds consisting of barite crystals with either galena or pyrite or even beds consisting chiefly of tennantite along with barite with or without chert.

Lindgren, on the basis of information available to him at the time, referred to an upper manto containing rich silver-copper ore with a lead manto beneath it. Our sampling shows that although there is a noticeable difference in the average metal content of the two mantos the difference is small and the contrast is much less marked than that between different portions of the same manto. Therefore Ahlfeld's explanation of the difference as due to different "primary depth zones" does not appear to be applicable and in any case, as Lindgren points out, seems improbable in view of the small vertical range involved. The results of composite samples are as follows:

	Pb.			Cu.		
	Av.	Max.	Min.	Av.	Max.	Min.
Upper Manto.....	4.1	20.3	trace	1.52	3.98	0.22
Lower Manto.....	6.1	9.5	3.0	1.52	3.88	0.38

The upper manto is richer in silver than the lower by fifty per cent. but within either manto the richest blocks contain up to six times the silver content of the poorer.

The foregoing descriptions apply to the silver and silver-lead ore bodies that have furnished the bulk of production from the mine. I am indebted to Mr. James A. Noble for data regarding occurrences of pyrite-enargite ore which have more recently been encountered some 200 meters south of the main workings in the direction of the monzonite plug. The ore here consists of cherty silica with massive pyrite and barite, followed by sphalerite, luzonite and enargite. It replaces a somewhat lower stratigraphic horizon than that of the silver ore bodies and on passing northward falls off in pyrite and the copper minerals until in the main workings it consists of only chert with a little barite. This sug-

gests a gradation northward from the intrusive from copper to silver-lead mineralization.

Gangue Minerals.—Gray to black chert with waxy luster is the earliest gangue mineral, replacing the calcareous shale. It is cut transverse to the bedding planes by veinlets of white to gray opalescent silica some of which contain vugs lined by quartz in comb structure. Other cavities are irregular and lined by drusy quartz and barite crystals—delicate transparent plates flattened parallel to the basal plane. Some reach two centimeters in diameter, but most do not exceed a few millimeters. Although later than the chert, some of the barite is earlier than the crystalline quartz, the " roots " of whose crystals may replace the barite.

Siderite occurs in places as botryoidal fillings in vugs. Fluorite has been found but is extremely rare.

Kaolin is a widespread alteration product of the argillaceous wall-rock. Some beds a meter or more thick are converted mainly into white or greenish-white kaolin. Between the kaolinized masses are the laminæ of the original shale which, in places, tend to bend around the kaolin areas, giving what might be called a bird's-eye texture.

Ore Minerals.—I shall attempt no addition to Lindgren's very complete description of the relations of the ore minerals. However, since the suite of specimens that I studied was different from his (and perhaps neither was fully representative) certain minor discrepancies deserve discussion. In particular, a generation of botryoidal sphalerite and galena was apparently not well represented in Lindgren's collection (though he does mention the late sphalerite) whereas the light-colored early sphalerite was rare in my suite.

My work suggests the following sequence:

Early sulphides: Pyrite, marcasite, sphalerite, tennantite and enargite, galena.

Later botryoidal sulphides: Sphalerite and galena followed by chalcopyrite.

Apparently still later: Stromeyerite.

Definitely supergene: Native silver.

There is an early coarse marcasite as Lindgren points out. Both this and the coarsely crystallized galena are coated by crusts of sphalerite. This is so clear in some of my specimens that Lindgren's statement: "galena always follows sphalerite" can be said to hold only within the early generation. There are at least two ages of pyrite, the second in small cubes which rest on galena. Although the galena is coated by fine-grained sphalerite the pyrite crystals stand out above the sphalerite crust, surrounded at their bases by sphalerite but not coated by it.

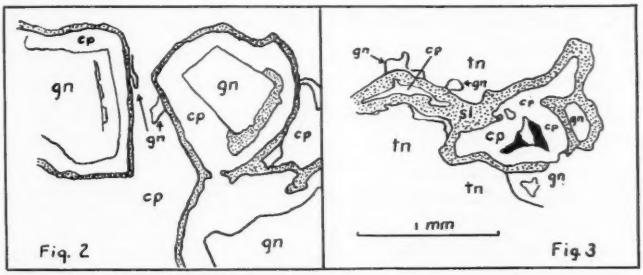


FIG. 2. Sketch of polished surface showing galena (*gn*) crystals surrounded by sphalerite (stippled) and chalcopyrite (*cp*).

FIG. 3. Vug in tennantite (*tn*) lined successively by (1) galena (*gn*), (2) sphalerite (*sl*, stippled), (3) chalcopyrite (*cp*), (4) stromeyerite (black). Part of stromeyerite replaced by native silver (white).

I am not sure just where Lindgren's "Late Specularite-Marcasite Phase" should be inserted in the above sequence. It was not represented in my material although I did find specularite with pyrite and kaolin in certain parts of the mine away from the main mantos. It may be contemporaneous with my "Later Botryoidal Sulphides."

Stromeyerite is consistently associated with tennantite and, as Lindgren shows, commonly replaces it. All stages of this replacement from partial to complete can be found. The replacement is highly preferential, the stromeyerite selecting tennantite to the almost complete exclusion of galena, sphalerite and chalco-

pyrite. In such cases the stromeyerite assumes of necessity the same space relations to the post-tennantite minerals that the original tennantite possessed and if its pseudomorphic character were not realized one might infer that the stromeyerite was, like the tennantite, older than the encrusting sulphides. Stromeyerite, however, is clearly later than any of the early sulphides. In a few cases, moreover, vugs lined by the crustiform sphalerite and galena are filled by stromeyerite suggesting that the silver mineral is even younger than the coatings.

Lindgren says, "McKinstry appears to have shown that some of the stromeyerite is earlier than the galena, sphalerite and chalcopyrite." McKinstry, it would appear, did not express himself clearly. What I intended to show [7] was just the opposite, viz. that stromeyerite is later than the galena, sphalerite and chalcopyrite.

This position in the sequence, if correct, is consistent with supergene origin for the stromeyerite though not in itself disproving hypogene origin.

Orcel and Rivera Plaza [8] consider the stromeyerite supergene and later than galena, blende and chalcopyrite, thus arriving independently at the same conclusion that I had reached. Ahlfeld, to the contrary, believes that the stromeyerite is hypogene. He considers it earlier than the late generation of blende and chalcopyrite because it is found, alone or along with tennantite, surrounded by the late sulphides. Were this criterion valid, the native silver could by the same reasoning be proved to be earlier than the chalcopyrite and blende for in numerous instances silver replaces cores of tennantite and stromeyerite without attacking the coatings. Yet everyone who has studied these ores agrees that the native silver is later than any of the sulphides. In support of hypogene origin for the stromeyerite, Ahlfeld states that the chalcopyrite that commonly coats graphically intergrown (graphisch verwachsenen) tennantite-stromeyerite is quite fresh "which

[7] Interpretation of Concentric Textures at Colquijirca, Peru. Am. Mineralogist, vol. 14, pp. 431–433, 1929.

[8] Orcel, J., and Rivera Plaza, G.: Étude microscopique de quelques minerais metallique de Pérou. Bull. Soc. Francaise de Min., vol. 52, pp. 91–107, 1929.

could hardly have been the case if it had come in contact with acid solutions." It is quite true that chalcopyrite associated with stromeyerite, appears fresh enough in polished section but this is true even of chalcopyrite that is associated with native silver and no one would deny that the silver is supergene.

Lindgren, like Ahlfeld, considers the stromeyerite hypogene apparently for the reason that he believes pseudo-eutectic intergrowths to be characteristic of hypogene replacement.[9] If this is an infallible criterion of hypogene origin the question is closed.

Certain field facts, however, suggest without necessarily proving, supergene origin for the stromeyerite. It is rarely if ever free from supergene native silver, though this may be due merely to the strong tendency of stromeyerite to break down. But furthermore it is characteristically found with chalcopyrite which is corroded and tarnished on surfaces exposed in vugs (although

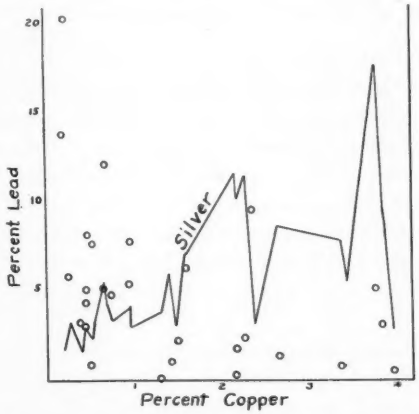


FIG. 4. Diagram showing variation of lead and silver with copper content in the sulphide ore. Each point represents an analysis of a composite sample of a block of ore measuring several thousand tons. Circles designate lead-copper content; the zig-zag line designates silver content on an arbitrary scale. An irregular decline of lead and increase in silver with increase in copper is indicated.

[9] Pseudo-Eutectic Textures. ECON. GEOL., vol. 25, pp. 1–13, 1930.

bright in polished section) in ore that has been etched and eaten away as though by acid waters. This strongly corroded ore rich in stromeyerite is especially abundant in certain stopes on the third level immediately under an area of oxidation whereas below these stopes, on the fourth level, tennantite, enargite and chalcopyrite are nearly free from etching and there, significantly, stromeyerite is rare.

Of more theoretical bearing but nevertheless suggestive, is the fact that copper in large aggregate amount has been leached from the oxidized zone along with silver. Although silver has been redeposited in the secondary zone, typical supergene copper minerals (bornite, covellite and chalcocite) are extremely sparse. If supergene copper did not deposit as stromeyerite, where has the copper gone and why was it not deposited under conditions that were obviously conducive to secondary silver enrichment?

OXIDATION.

Depth.—The bottom of oxidation varies from bed to bed as well as along the strike. At a depth of 60 meters (100 m. on the dip of Veta Principal) all the ore is oxidized except for a few upward-protruding peak-shaped areas.

Some oxidation has reached the fourth level (120 m.) although most of the ore here is fresh. The transition from gossan to fresh galena is abrupt and takes place within a few meters along the strike. Where cross-folding has formed a trough in the flat-dipping Veta Principal, oxidation reaches its greatest depth.

There is reason to believe that the surface waters descended along the bedding, confined by impervious shale strata. It is not uncommon to find one bed unoxidized while the adjoining one is thoroughly altered and the reason for this can sometimes be found in differences in mineralogical nature of the respective beds. Where the ore is pyritic and would, on oxidation, have yielded abundant sulphuric acid, the oxidation goes deeper than in galena orebodies. Again where sulphides are so abundant as to have used up oxygen rapidly the oxidation does not extend as

deep as where mineralization is sparse. Outside the sulphide-bearing beds the limestone shows very little iron stain. The confinement of the descending solutions to their respective beds, thus preventing dissipation of the silver, may be one reason for the extraordinary richness of the secondary zone.

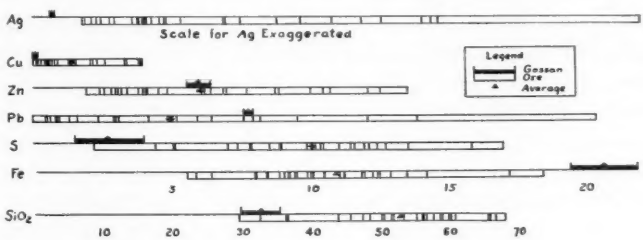


FIG. 5. Graph showing range and average of content of various elements in ore and gossan. Each small vertical line represents a determination in a composite sample. (Silver and silica are plotted on different scales from the other substances.)

Chemical Changes.—A number of partial analyses made for metallurgical purposes by A. Rizo Patron serve to show the chemical difference between the ore and the overlying gossan. In all, thirty-one composite samples were analyzed. Each composite represented a block of ore or of leached gossan and each was made up from a large number of channel samples (in some composites several hundred) by taking a weighed amount of pulp

	ORE.			GOSSAN.
	Average.	Maximum.	Minimum.	Average.
SiO_2	52.7	68.0	29.7	32.8
Al_2O_3	6.6	11.0	2.7	7.4
Fe	10.9	18.4	6.4	20.6
BaO	2.4	6.8	0.9	trace
CaO	0.5	1.9	0.0	1.0
MgO	0.9	1.7	0.3	1.3
S	10.0	17.0	2.2	2.3
Zn	6.1	13.5	1.9	6.0
Pb	5.0	20.3	0.4	7.7
Cu	1.5	3.98	0.22	0.12

from each sample in proportion to the width of the channel. In the first column, above, is the average of twenty-nine composites from blocks of sulphide ore. The second and third columns give the maximum and minimum percentages respectively which any ore block showed. The fourth column is the average of two composites representing blocks of gossan.

Conclusions from these analyses should be drawn with caution, since it is not certain that the gossan blocks were, before oxidation, the exact chemical equivalent of the average (sulphide) ore block. But the number of ore blocks sampled is so large that the former composition of the gossan blocks surely lies somewhere within the range represented.

Striking, but not surprising, is the leaching of copper and sulphur. If it were permissible to present silver values they would show a corresponding diminution from high assays in the ore to very low in the gossan. More unexpected is the leaching of barium—neither of the gossan blocks shows more than a trace. The writer has seen in two other oxidized ore bodies (Parral and Las Damas, Chihuahua) disappearance of barite as evidenced by partly etched barite blades with negative pseudomorphs of barite in ironstained quartz. Noble [10] also has noted leaching of barite at Yauricocha and Cerro de Pasco, Peru.

Lead remained in the gossan as would be expected, but it is surprising that the zinc showed so little leaching. That the gossan blocks sampled were originally exceptionally high in zinc is an improbable explanation because in this mine high zinc is generally accompanied by particularly high lead.

Regarding alumina, lime and magnesia, the analyses are not significant since the amounts in the gossan are within the range of variation in the ore blocks.

The following table brings out the definite decrease in the ratio of silica to iron accomplished by oxidation:

	Silica: Iron Ratio	
	Ore blocks	Gossan blocks
Average	4.8	1.6
Maximum	11.0	1.8
Minimum	2.3	1.4

[10] Noble, J. A.: Personal communication.

Obviously this may have been brought about either by leaching of silica or by addition of iron to the gossan or both. A simple calculation shows that conversion of the average ore block into the average gossan block without importation of iron would require the removal of two-thirds of the silica. On the other hand the same conversion by addition of iron without any leaching of silica would require importation of almost double the quantity of iron present already. The mobility of iron as sulphate would favor the latter. Even if the gossan has been derived from ore of the lowest silica-iron ratio shown by any block, there was a relative decrease in the silica-iron ratio.

Mineralogical Changes.—The pyritic ore alters to a reddish claylike limonitic gossan. Galena, as would be expected, changes to anglesite which is surrounded by cerussite, often beautifully crystallized, as individual prisms or as pseudo-hexagonal twins. Strangely enough, tiny crystals of sphalerite, clear-cut, and showing no signs of etching, are found in the oxidized mineral—one of them was actually perched on a cerussite crystal! It seems remarkable but inescapable that blende crystals have either withstood alteration better than galena or were deposited after the intense oxidation. Cerargyrite and covellite were noted, each in only a single instance, as oxidation products of stromeyerite.

Below the zone of complete oxidation a number of the minerals show effects of etching, evidently by descending solutions. Galena succumbs readily to this attack except where it has been protected by films of the late botryoidal sulphide. Similarly, tennantite has been protected by chalcopyrite films, but in places the tennantite has been dissolved away from within the crust of chalcopyrite which, under such conditions is generally porous and coated with a black tarnish or with a sooty mineral which I took to be stromeyerite [11] although I could not identify it as it is always inseparably mixed with chalcopyrite remnants and wire silver.

Relation of Enrichment to Structure and Topography.—On the limbs of the Mercedes-Chocayoc anticline, which has only

[11] It seems unlikely that it is chalcocite. Lindgren says chalcocite is not abundant and I found none at all though I found plenty of identifiable stromeyerite along with the tarnished chalcopyrite.

recently been exposed to erosion and part of which is still "blind," enrichment as evidenced by presence of native silver, is much less pronounced than on Veta Principal which has long been exposed to leaching. The richest native silver-stromeyerite stopes in the mine are under the lobe of gossan which extends down the cross-fold in Veta Principal.

Physiographically, Colquijirca, like Cerro de Pasco, lies on the "Nudo de Pasco," a remnant of the old Puna [12] erosion surface between the eastern and western ranges of the Andes, and between the magnificent canyons which are encroaching on it from the north and south.

As contrasted with the western slope of the Cordillera where erosion has been too rapid for the survival of secondary ores, the mildly dissected Puna surface has been favorable to preservation of the enriched zone. The mine is at the head of one of the broad gravel-filled valleys of the Junin topographic stage which have been cut into the mature Puna surface. The water table may well have varied in elevation from bed to bed, due to different rates at which water was supplied by percolation and removed by artesian flow, and from time to time during the cutting of the valley and deposition of the gravel filling. The result was a marked irregularity in the depth of oxidation and enrichment.

ORIGIN OF THE ORE.

Although chert was in general earlier than the sulphides these two phases of mineralization must have been closely related since no chert is found without some sulphides and no sulphides occur without some chert. The mineralization took place after the folding since:

1. The gouge that occurs between beds and was probably formed by gliding during folding contains no drag sulphides.

2. Neither the chert nor the crystals of barite and other minerals which line vugs are crushed. (Although folds of large radius would not necessarily have shattered the beds everywhere, it seems unlikely that the slipping between beds, which accom-

[12] McLaughlin, D. H.: Op. cit.

panied folding, could have taken place after mineralization without some breaking of the delicate crystals.)

3. It is difficult to imagine a series of interbedded brittle chert bands and incompetent shale beds folded without some fracturing of the chert and drag-folding of the shale.

4. The axial fault in the Mercedes-Chocayoc anticline, which is probably related to folding, was present when mineralization occurred as it is silicified in the neighborhood of mineralized beds (although not elsewhere).

The ore deposit is believed to have been localized by the Marca-Punta porphyry stock because:

1. The ore of two other mines (San Gregorio and Unish) occurs close to or within this same stock.

2. Chemically similar ores of copper and silver with high arsenic and low gold content occur with petrographically similar intrusives throughout the region.

3. There is a suggestion of gradation from copper ores near the stock to silver ores farther away.

The hydrothermal alteration of the monzonite suggests that after consolidation the intrusive was permeated by solutions from a deeper source, which also found their way into the sediments. It is, therefore, probable that the porphyry mass or its margins served as the channelway for the ascent of ore solutions. That the parent magma of the porphyry was the source of the metals is less definitely indicated but is a plausible hypothesis.

Since no mineralized fractures that could have served as feeders were found (despite ample crosscutting under the ore bodies) the conclusion is that the ore-solutions entered along the beds from the margins of the stock, travelling gently upward along the pitch.

The primary mineralization is marked by certain unique features such as the deposition of marcasite at an early stage, the abnormally late appearance of much of the sphalerite, and the rarity of carbonates and of the ruby silvers (proustite is reported but is rare) despite abundance of arsenic in the deposit.

The abundance of barite indicates presence of the sulphate

radical in large quantity, a circumstance which, following Butler's [13] suggestion, may be explained on the assumption that solutions which would tend to precipitate ferric oxides at high temperatures will at lower temperatures deposit iron as sulphide, while the oxygen combines with sulphur to form sulphates. In the absence of sufficient bases to combine with the sulphate radical, sulphuric acid might tend to form at certain stages, and under such conditions, marcasite might be deposited. The same acid conditions might delay the deposition of some of the sphalerite, decompose alkaline earth carbonates and inhibit the deposition of ruby silvers which do not form under acid conditions.[14]

Alunitic alteration in the monzonite stock and extensive kaolinization of the sediments likewise point to acidity of the solutions at certain stages.

Thus, the peculiarities mentioned above could all be explained by decrease in alkalinity of the solutions at certain stages of ore deposition.

SUMMARY.

The ore bodies have resulted from the replacement of a group of beds in a folded Tertiary (?) shale-limestone formation. The largest shoots are localized by cross-flexures in the beds. A monzonite stock is believed to have been the conduit for mineralizing solutions which entered the limestone along the bedding at some stage later than the folding, silicified and kaolinized the beds and deposited sulphides. The solutions were high in sulphate and perhaps were acid at certain stages as suggested by a number of peculiarities of the mineralization.

Comparison of analyses of the gossan and sulphide ore show that oxidation processes were of the usual sort except that barium is leached whereas zinc is retained in the gossan. The proportion of iron to silica in the gossan is higher than in the ore.

The oxidizing solutions travelled down the bedding and the

[13] Butler, B. S.: Primary Sulphate Minerals in Ore Deposits. ECON. GEOL., vol. 14, p. 581, 1919.

[14] Ravicz, L. G.: ECON. GEOL., vol. 10, p. 378, 1915. Grout, F. F.: ECON. GEOL., vol. 8, p. 429, 1913.

depth of oxidation is strongly influenced by the nature of mineralization in individual beds. Impervious strata, by preventing dissipation of the descending silver-bearing waters, may be partly responsible for the exceptional richness of the secondary ore.

The ores have been generously enriched by supergene native silver and certain evidence suggests that stromeyerite may also be supergene although Lindgren and others consider it hypogene.

ACKNOWLEDGMENTS.

I am deeply grateful to Drs. L. C. Graton and D. H. McLaughlin for many valuable suggestions and criticisms during the course of the investigations. Dr. Waldemar Lindgren generously allowed me to look over his suite of specimens and discussed the problems of sequence. Mr. J. A. Noble has very kindly supplied me with information regarding the newer workings and has criticised parts of this paper in the light of his own field work. I have furthermore had the benefit of an unpublished report by Drs. M. N. Short and R. W. Goranson who made the first examination of a suite of specimens.

To the Negociacion Fernandini owners of the property, and to the Cerro de Pasco Copper Corporation on whose behalf the examination was made, I am indebted for permission to publish this paper. Senores Remy, Arce, Diaz and Baertl extended unstinting hospitality and courtesies at the mine.

120 WALL ST.,
NEW YORK CITY,
May 18, 1936.

DISCUSSION AND COMMUNICATIONS

THE INVESTIGATION OF THE CLEAVAGE OF GRANITES

Sir: In the May number of this journal, J. F. Bell presented a paper in which he suggests that petrofabric methods should be used as a basis for the study of the "cleavage" of granites, and he places particular emphasis on the use of the universal stage in determining the orientation of minerals and microstructures. I do not agree with Bell's contention. Without wishing to belittle the contribution that petrofrabric studies have made and may make to structural petrology, I should like to point out that many of the features emphasized in petrofabrics have been observed for a long time. New names have been given to some of them, but so far there has been little improvement in explanation offered for them. And, until the explanations are improved, petrofabrics must be regarded as contributing to the geometry rather than the genesis of rocks.

I question whether a thin section is the best unit in which to study the cleavage of granites. At the best it has only a small area and has been ground to a thickness of 1/1000 inch. The grinding of the section has developed cracks, that may or may not have been in the original rock. It has even been suggested that twinning in feldspar has developed during the preparation of the thin section, and certainly the cracks so formed are common. The orientation of minerals with perfect cleavage may be fairly accurately determined without a universal stage by observing the direction of the trace of the plane in the thin section, and the inclination of the plane may be determined by using a high-power objective and observing the displacement of the trace of the cleavage on racking the objective up and down.

It should be obvious that the best method of study of the cause of cleavage is observation of the cleavage faces themselves, rather than a prepared section. In a coarse-grained granite the actual path taken by the cleavage is clearly visible. The behavior of each mineral in the path of the "break" may be studied. If more quantitative observations are desired, the orientation of the plane surfaces on the "break" may be determined with a student (Wollaston) type goniometer. I examined a granite by this method in 1930 and was surprised to find that the cleavage of biotite did not lie in the rift surface. The approximate orientation of cracks in quartz may be determined either by removing the plate of quartz from the rift surface and examining it under the microscope or examining thin sections oriented with respect to the cleavage direction in thin section. Approximate orientations may be judged from the interference color and the thickness of the specimen or from the interference figure. Universal stage determinations are more accurate, but they cannot determine the positions of microstructures with reference to the horizontal crystal axes of quartz.

The mere statistical examination of microstructures in granite, unless accompanied by proof that they do cause the cleavage, is no more valuable than the qualitative observation of the same features. The fact that a certain number of mica plates are parallel to a cleavage face does not prove that they cause the cleavage unless the cleaved surface shows that the break was pre-determined by the mica. It is necessary to prove that other factors were not operative to establish that the parallel orientation of mica is alone responsible.

Many writers have insisted that different causes may be responsible for the cleavage of granites in different regions. No doubt, in some places, the rift is parallel to the plane in which the mica plate lies, as postulated by Bell, but it so happens that this is not the case in most quarries in the granites of the Laurentian area in Quebec. The fractures in quartz are well marked in natural sections transverse to the rift, and the rift surface is seen to contain a great many of them. I prefer an interpretation based on such megascopic rather than on microscopic features.

On page 274 Bell says, "Both of these articles based upon statistical measurements stand as direct contradictions to Osborne's statement that the rift, grain, and hardway in the Laurentian granites are not related to the jointing." This is a misinterpretation of a statement, "The joints are quite separate and distinct from the cleavage directions." In the next paragraph[1] I described the *ac* or *Q* joints parallel to the hardway. My reason for including the statement was that in some discussions joints had been confused with the cleavage. If Bell had said that the rift and sheet joints were independent of the other joints in most of the granites of the Quebec Laurentian, the statement would have been true. I described the Laurentian area of Quebec in the Annual Report of the Quebec Bureau of Mines, 1932, Part E, and 1933, Part E. The maps and diagrams show that the grain —where it coincides with the *s* plane or the foliation—and hardway are generally parallel to prominent joint systems other than those of the sheets. In 1934 and 1935, G. K. Lowther and I made a field and petrofabric analysis of some rocks from the Shawinigan Falls district, Quebec, and found a generally good agreement between some of the fabric elements and the joints. We plotted the poles of joints on the Lambert equivalent projection in the same manner as Maroschek did. Incidentally Bell's statement that "an equal-area stereographic net" was used is erroneous. The equal-area net used for petrofabric analysis is the Lambert Equivalent projection; a stereographic projection is conformal and of quite different properties from the equivalent projection. Unfortunately properties of the two projections cannot be combined. In the Shawinigan Falls district there are no granites with a good rift, but some plutonic rocks with 10 to 15 per cent quartz show a faint rift, and it does not coincide with any fabric element. The metamorphic rocks, with some exceptions, break most easily along the *ab* plane.

In conclusion I should like to say that petrofabric methods have been used on problems in the petrography laboratory of McGill University, and some of the results are not so clearcut as might

[1] ECON. GEOL., vol. 30, p. 559, 1935.

be desired. Quartz from sharply folded metasedimentary rocks of the Temiskaming series does not show a lattice orientation that can be correlated with the geological occurrence of the rocks. Petrofabrics failed to give a cleancut method of distinction between some quartz veins and quartzite in the Temiskaming rocks. On the other hand, the petrofabric method has given good results on some problems. It is natural that in the attempts to find applications of a new method some experiments should be made, but I doubt if any of the petrofabric methods yet evolved can give a true and complete solution of the complicated problem of the cleavage in granite. It may supplement other observations; I have on hand, waiting petrofabric study, one specimen from a granite in which I was uncertain of the cleavage relations, but for most of the granites the examination in the field gives a clear picture. With regard to the relationship of the joints to cleavage, the attitude of the joints is likely to be observed and it does not matter what they are called. The quarryman's "hardway slicks," Cloos's "*Q* joints" and Sander's "*ac* cracks" are all understandable terms and equally good until the origin of the various joints is more thoroughly explained.

F. F. OSBORNE.

McGILL UNIVERSITY,
MONTREAL, QUE.,
July 10, 1936.

RETROACTIVE MOVEMENT ALONG FAULTS.

Sir:—There has been some mention in geologic literature of reversal movements[1] and oscillation movements[2] along faults, and it is thought that the possibility of such occurrences may be more common than is generally recognized. A fault, as exposed underground in extensive mine workings presents, perhaps, the best condition for the determination of complex movements.

[1] Buwalda, J. P.: Reversal in direction of vertical component movement along faults. Geol. Soc. Amer. Bull., vol. 42, p. 187, 1931; Pan-Amer. Geologist, vol. 51, p. 336, 1929; vol. 55, p. 64, 1931.

[2] Sutton, A. H.: Fracturing and movement in rocks without apparent displacement. Science, New Series vol. 73, p. 264, 1931.

Examination of several faults in the Mother Lode region and in northwestern California demonstrated good evidence of reversal in the direction of movement and possible oscillation of movement, although the amount of final displacements could not be ascertained.

In the field, suspicion of reversal in the direction of movement would be greatest where the offset of identifiable segments of some body is observed to be relatively slight against a significant fault. That is, there may be reason to believe that the displacement of the body is greater than the nature of the fault may indicate. Such a condition would be the proximity of identifiable segments of a dike, vein, or stratigraphic member that has been offset by the fault.

A pronounced and significant fault fissure may be indicated by (1) a wide thickness of gouge, (2) a wide zone of brecciation or shearing, (3) multiple walls of slipping or (4) a complication of any of these conditions. Absolute determination, however, would involve the finding of actual reversal in the direction of movement as shown by the surface features on the walls of the fissure, by a complication of drag structures, or by any other method for the determination of different fault movements. Intersecting striae on the slickensided surface of a fault plane indicate varying directions of recurrent displacement of one wall relative to another but they do not necessarily indicate reversal in the direction of movement of the respective walls. The most conclusive evidence, therefore, of these complex movements is demonstrated best where the proximity of the faulted segments of a body is supported by the record of such movements on the wall of a fault.

Reversal in the direction of movement or oscillation of movement would be greatest where the direction of opposite maximum displacements has been parallel or nearly so. Probably no reversal in the direction of movement along a fault would totally compensate all previous displacement but any such movement would tend to have this effect. Further, the result of any later opposite movement would probably not be greater than the important movements that instigated the fault.

In as much as the foregoing conditions seem probable, the terms *retroactive* and *oscillatory* may be used to designate these respective types of fault movement, where it is possible to distinguish them. In either case, a fault would ordinarily be designated normal or reverse as to class, according to the direction of the last important displacement. Close examination, however, might demonstrate that movement along the fault has been rather complex. Perhaps, then, in some special cases, the above terms may be applied as a class name for a particular fault.

Obviously, the cause for complex movement along a fault depends on the nature of the diastrophic events in the region of the fault. It is possible that these types of fault movement may apply well in the roofs of intrusions and the cause here may be quite apparent. Faults will form in the solid outer shell of an intrusion and in the wall rock in response to demand for space. As the intrusion cools, contraction must take place with reversal in the direction of movement along the faults. Where a composite intrusion is forming, the direction of movement may change several times giving oscillation movements along a fault. This possibility should apply well to the generation of ore veins of igneous origin.

In fact, much economic importance may be attached to the possibility of the above conditions in regard to faulting. In the growth of ore-bearing veins by a process of accretion along an original fault fissure, it seems quite likely that in many cases the complicated and intricate structures found underground in these veins and between them and adjacent wall rock may be due, in a large part, to retroactive or possible oscillatory movement along the formational fault fissure. Also, a consideration of these possibilities may be important in the pursuit of orebodies subjected to post-mineral faulting.

HOMER D. ERWIN.

SUSANVILLE, CALIF.,
August 1, 1936.

REVIEWS

Origin of the Anhydrite Cap Rock of American Salt Domes. By MARCUS I. GOLDMAN. U. S. Geol. Surv., Prof. Paper 175–D, 1933, pp. 83–114, pls. 24–42.

Although considerable time has passed since the publication of this paper, a review of it is desirable, since it is one of the few papers on the subject of American salt dome cap rock based on a study of cap rock material rather than on philosophical considerations. Dr. Goldman's[1] first paper was also based on a study of actual cap rock material. It was largely a petrographical study and considered only slightly the broader geological implications. The present paper does consider the broader geological implications, and consequently different conclusions have been reached from those presented in the first paper.

Dr. Goldman postulated two origins for the anhydrite cap rock and weighed the evidence in his consideration of each. The two are "(1) that the cap rock is derived from an original bed of sedimentary anhydrite which overlay the salt of the salt stock in depth and was pushed up on top of the stock during its intrusion into the overlying beds, and that during its upward progress the bed of anhydrite was brecciated, and the breccia, recemented, makes up the cap rock; (2) that it is formed by the cementation and consolidation, on top of the salt stock, of grains of anhydrite and fragments of anhydrite rock freed from the salt stock by solution at its upper end." The first he termed the "sedimentary hypothesis" or "sedimentary origin" and the second the "residual hypothesis" or "residual origin."

One of the characteristic textures of anhydrite cap rock is the abundance of parallel banding, which, in proximity to the salt, is more or less parallel to the salt surface, although in zones of collapse breccia[2] may or may not be parallel to the salt surface. These bands Dr. Goldman terms "katatectic bands" and the surfaces "katatectic surfaces."

After weighing the evidence for and against each postulated origin, Dr.

[1] Goldman, M. I.: Petrography of Salt-dome Cap-rock. Am. Assoc. Pet. Geol. Bull., vol. 9, no. 1, pp. 42–78, 1925; also in DeGolyer, E. L. and others: Geology of Salt-dome Oil Fields, pp. 50–86, 1926.

[2] Hanna, M. A.: Secondary Salt-dome Materials of Coastal Plain of Texas and Louisiana. Am. Assoc. Pet. Geol. Bull., vol. 14, no. 11, p. 1470, 1930.

Goldman advocated the residual theory for the formation of the anhydrite cap rock. The essential steps in the formation of the anhydrite cap rock are discussed, in part in considerable detail, and supported by photographs.

The salt stocks contain, beside the sodium chloride, varying amounts of disseminated crystals of anhydrite, either as scattered crystals or as bands in which the crystals are concentrated. In the bands the crystals are separate individuals in a salt matrix and break down to anhydrite sand when the salt is leached. Dr. Goldman discussed the possibility of bedded anhydrite in the salt stocks. He cited some published records, but has seen no such material from the salt stocks. As far as the reviewer's observations are concerned, from rather extensive core material and from the salt mines, no bedded or sedimentary anhydrite has been found.

Water in contact with the periphery of the salt stock readily dissolves the salt, leaving a residue of the much less soluble anhydrite. As the salt continues to be dissolved, there results an accumulation of residual anhydrite. This accumulated anhydrite sand becomes compacted with the collapse of the overburden or with an upthrust of the salt, and terminates a cycle. A new cycle is incepted with the removal of more salt by solution. With each new compaction of anhydrite sand a katatectic band is formed between cycles. In this residual material any sedimentary or bedded anhydrite in the salt stock would also accumulate in the residue. Dr. Goldman gave photographs of small fragments, which he believes to be of brecciated bedded anhydrite. He considered the ways in which the bedded anhydrite may have become brecciated, *i.e.* (1) intraformational brecciation in the original salt series, (2) brecciated at the katatectic surface, (3) or in the flowage in the salt stock. He eliminates the former, but is unable to determine whether the second or third was the cause.

The postulation that the katatectic bands are due to shearing is eliminated, although it is recognized that shearing does occur and might cause somewhat similar bands. The character of the bands, however, would be different.

In the discussion of the thickness of the cap rock and the presence or absence of cap rock, the paper seems to the reviewer to be inconclusive, not because of faulty reasoning, but because of insufficient information. For instance, some published reports show no cap rock between the surrounding sediments and the salt stock. The reviewer believes that such records are based on incomplete information. The zone of residue may be very thin, and with the salt reached unexpectedly, the core barrel may not be on until it is too late to secure a contact sample. Often the anhydrite is recorded as rock. Again the anhydrite may be present as anhydrite sand and is washed from the core barrel during the process of securing the sample. For these reasons the reviewer is of the opinion that the negative evidence now available is insufficient to conclude that an

anhydrite or gypsum cover is ever absent. In the reviewer's experience it has always been present where a contact was well sampled, even to the depth of present drilling. The possibility of its absence is recognized where the salt has recently moved, but its absence otherwise is very doubtful.

Dome stripping has occurred on several of the Gulf Coast salt domes, and accounts for certain of the peculiarities not cited by Dr. Goldman. Another factor which none of us have considered sufficiently in the subject of the origin of cap rock is the variation in the anhydrite within the salt stock, both as to character and quantity.[3]

Dr. Goldman's paper is an excellent one on the subject of origin of anhydrite cap rock, and is very much in agreement with the reviewer's conclusions.[4] Virtually all those who have actually studied salt dome cap rock material are, in general, in agreement with the conclusions reached by Dr. Goldmon. Dr. Levi Brown has published a paper since the appearance of Dr. Goldman's paper under review, in which he still supports a sedimentary origin for the cap rock.[5] The reviewer is of the opinion that the mass of data which has been accumulated is sufficient to reject Dr. Brown's contentions as untenable, although very interesting.

MARCUS A. HANNA.

GULF OIL CORPORATION,
HOUSTON, TEXAS.

Down to Earth. By C. CRONEIS and W. C. KRUMBEIN. Pp. xvii + 501, many figures, pls. 64. University of Chicago Press, Chicago, Ill., 1936. Price $3.75.

This book is an attempt of the authors to write a text that will be more attractive to the reader than the conventional introductory text book of geology. Their purpose was to "enliven the subject without in any sense writing it down. . . . We have felt that the treatment of the subject should not be more dull than the science itself," which they consider should be particularly interesting to the layman and the beginning student. The text "attempts to develop a more analytical attitude" toward the science than do most introductory texts, and "more rigorous treatments of many geological phenomena" than is commonly the case. The authors have succeeded in making a volume that is perhaps easier reading than the ordinary text-book, but it may be questioned whether its wordiness

[3] A paper is in preparation by Albert G. Wolf and the reviewer on the subject of salt in the salt stocks.

[4] Hanna, M. A.: 1930, op. cit. Hanna, M. A.: Geology of Gulf Coast Salt Domes. Problems of Petroleum Geology. Am. Assoc. Pet. Geol., 1934, pp. 629–678.

[5] Brown, L. S.: Age of Gulf Border Salt Deposits. Am. Assoc. Pet. Geol. Bull., vol. 18, no. 10, pp. 1227–96, 1934.

may not in some places obscure the reasoning employed. In a few places the treatment of the subject matter seems to lack dignity, but perhaps this is intentional—a means to promote popularity.

The illustrations are worthy of note. The text figures "have been culled chiefly from the ancient works in geology or other fields." Many others are block diagrams or graphs, which might well have been more fully explained in their titles, or humoresque sketches that will appear out of place in a serious text on geology. It might have been more informational to the users of the book if some of the illustrations "culled from the ancient works" had been replaced by reproductions of recent photographs that would show the phenomena illustrated more nearly as they are than was shown in the old drawings. The more significant illustrations are sixty-four pages of rotogravure pictures, inserted in groups of sixteen at four different places in the text. Most of them are excellent and do much to clarify the text.

The volume may not serve as a satisfactory text in most colleges, but it will certainly be valuable as a supplement to the text used, since it deals with many phases of geology, especially on the theoretical side, that are simply referred to in the conventional text. It will probably also be more interesting to the general reader than the ordinary introductory text in geology. One serious objection to it is its great weight.

W. S. Bayley.

Historical Geology. By Walter A. Ver Wiebe. Second Edition. Pp. v + 316, figs. 238. John S. Swift Co., Inc., St. Louis, Mo., 1935. Price, $3.00.

This second edition follows the plan of the original in presenting the latest portions of geologic history first with the hope that the interest of the student may be maintained at a high point throughout the course. The book begins with an introductory chapter in which principles of stratigraphy, paleontology, paleogeography, evolution and correlation are discussed. This is followed by discussions of the Quaternary, Tertiary, Mesozoic, etc. For each era the periods are considered in their natural order rather than in reverse, as is the plan for the eras. The origin of the earth follows, and the book ends with a chapter on the National Parks. One commendable feature is the better balance between eastern and western North America rather than the over-emphasis on the eastern portion which appears in many text books. Although tables of formation names are not of great importance in an introductory text in Historical Geology, it seems unfortunate that there should be such discrepancies between the generally accepted systemic classifications and those given in this book. As a whole the book is not attractive in appearance. Printing has been by the planographing method and is not particularly good. In many

places the lines are too close for easy reading and in the copy seen by the reviewer, several pages are so blurred that reading is difficult. Although the illustrations have been well selected to bring out points of the text, the reproductions are in general very poor.

A. H. SUTTON.

UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS.

Schwimmaufbereitung. By W. PETERSON. Pp. 337, figs. 93. Theodore Steinkopff, Dresden and Leipzig, 1936. Paper, 18 Rm.

Dr. Peterson's treatise on flotation is intended not only for the use of technicians but is also for those who are interested in the theoretical aspects of the subject, and it is hoped will also be of interest in the study of colloidal chemistry. After a brief description of the tools employed in flotation methods, 127 pages are devoted to the theory of the processes from the standpoint of colloidal chemistry, including a discussion of the chemical and physical conditions influencing their results. Then follow 169 pages on the media used in accomplishing flotation, including their composition, chemical structure, and physical and chemical properties, and on the nature and function of activation. The next 45 pages comprise a section on the sensitivity of various minerals and ores to the usual flotation media, and remarks on the efficiency, etc., of the processes employed. A list of 856 articles on the different phases of flotation, the properties of the media that have been suggested and the patents that have been granted concludes the volume.

W. S. BAYLEY.

BOOKS RECEIVED.

L. B. RILEY.

Geologic Maps of the Musoma District, Tanganyika. G. M. STOCKLEY. Geol. Surv. of Tanganyika Territory. Dar es Salaam, 1935. In colors, 1:125,000. The geology of these two sheets (Eastern Musoma Goldfields and Southern Musoma Goldfields) has been described in Bull. 7 of this survey.

Geological Survey of Uganda, Bull. 2. E. J. WAYLAND, director. Pp. 81, figs. 12, map. Entebbe, 1935. 5s. A series of twelve articles on various phases of stratigraphy, petrology, structural and economic geology, besides a bibliography of the geology of Uganda and a provisional geologic map. Deposits of gold, tin, and copper are among the economic possibilities.

Geological Survey and Mines Department, Sierra Leone, Report for 1933 and 1934. J. D. POLLETT, officer-in-charge. Pp. 22. Freetown,

1935. 2s 6d. The mineral production for 1934 had a value of more than one and a half million dollars, from placer gold, diamonds, iron ore, and platinum. The gold is derived from quartz-pyrite-tourmaline stringers, and from banded ironstones, in a metamorphic complex.

Contributions in Geology. CARL TOLMAN, editor. Pp. 97, pls. 7, figs. 14. Washington Univ. Studies, New Series, Sci. and Tech. No. 9. St. Louis, 1936. $1.00. Five papers, four concerned with stratigraphy and paleontology. The fifth—Heavy Accessory Minerals of the Granites of Missouri, by Carl Tolman and H. L. Koch—presents methods of sampling, preparation and examination.

Geology of Texas, Vol. II (Structural and Economic Geology). E. H. SELLARDS AND C. L. BAKER. Pp. 884, pls. 8, figs. 40. Univ. of Texas, Bull. 3401, 1934. Austin, 1936. An excellent summary of the structural geology of Texas. Several chapters on mineral resources have been contributed by members of the U. S. Geol. Survey. The potash deposits receive a very extensive treatment.

Handbuch für den deutschen Braunkohlenbergbau, Bd. II. G. KLEIN AND H. W. FOX. Pp. 872, figs. 968, 39 line drawings in separate cover. Wilhelm Knapp, Halle (Saale), 1935. This volume of the third edition of this treatise deals with the technical details of the mining of lignite.

Quinquennial Review of the Mineral Production of India, 1929–1933. L. L. FERMOR, director. Pp. 453, pls. 7. Geol. Surv. India, Records, vol. 70. Calcutta, 1936. Besides statistics of production there are interesting descriptions of many of the producing areas.

Nickel no Brazil. L. J. de MORAES. Pp. 168, pls. 15, figs. 22. Brazil, Serviço de Fomento da Producção Mineral, Boletim 9. Rio de Janeiro. 1935. A careful study of Brazil's nickel deposits, including petrographic descriptions.

Mineral Industry of Alaska, 1934. P. S. SMITH. Pp. 91, figs. 3. U. S. Geol. Surv. Bull. 868–A. Washington, 1936. 10 cts.

Surface Water Supply of the United States 1934: Part 4 St. Lawrence River Basin. N. C. GROVER AND OTHERS. Pp. 159. U. S. Geol. Surv. Water-supply Paper 759. Washington, 1936. 20 cts.

Soil Survey of Ohio and Switzerland Counties, Indiana. B. H. HENDRICKSON AND OTHERS. Pp. 60, map. U. S. Dept. Agriculture, Bur. Chem. and Soils, ser. 1930, no. 37. Washington, 1935. 30 cts.

Illinois Mineral Industry in 1934. W. H. VOSKUIL AND A. R. SWEENY. Pp. 57, figs. 3. Ill. Geol. Surv. Rept. of Investigations 39. Urbana, Ill., 1936. Statistics.

The Geology and Oil and Gas Possibilities of parts of Marion and Clay Counties. J. M. WELLER AND A. H. BELL. Pp. 54, figs. 10. Ill. Geol. Surv., Rept. of Investigations 40. Urbana, Ill., 1936. Two domes and two anticlines in the central portion of the Illinois Basin.

The Competitive Position of Illinois Coal in the Illinois Coal Market Area. W. H. VOSKUIL. Pp. 112, pls. 3, figs. 3. Ill. Geol. Surv. Bull. 63. Urbana, Ill., 1936.

Subsurface Studies in Northeastern Kansas. J. W. OCKERMAN. Pp. 78, pls. 13, figs. 4. Kan. Geol. Surv. Bull. 20. Lawrence, Kan., 1935. Structure, stratigraphy, and well logs of the Forest City Basin.

Kansas Geol. Surv. Bull. 21. Part I: The Geology of Johnson and Miami Counties. N. D. NEWELL. Part II: The Geology of Wyandotte County, Kansas. J. M. Jewett and N. D. Newell. Pp. 212, pls. 20, figs. 2. Lawrence, Kan., 1935. Stratigraphy of the Pennsylvania System in eastern Kansas.

Opawica-Chibougamau Map Area, Northern Quebec. G. W. H. NORMAN. Pp. 24, map. Can. Geol. Surv. Prelim. Rept. 36–6. Ottawa, 1936. Sulphides and gold-bearing quartz in pre-granitic rocks. The areas of pre-granitic rocks are described as an aid to exploration.

Quebec Bureau of Mines, Ann. Rept. 1934. A. O. DUFRESNE, director. Part A: Mining Operations and Statistics. Pp. 202, pls. 9, figs. 5 (maps). Quebec, 1935. The total value of the mineral production showed an increase of 11.2 per cent. in 1934 as compared to 1933. Madeleine Lake gold discovery and mining properties in the Chibougamau Opemisca region are described by G. S. MacKenzie.

Quebec Bureau of Mines, Ann. Rept. 1934. J. A. DRESSER, directing geologist. Part C. Pp. 68, pl. 1, 4 maps. Quebec, 1935. Four papers on the geology and ore deposits of: Sabourin Map-Area, Témiscamingue Co., by B. T. DENIS; Travers Lake Map-Area, Témiscamingue Co., by J. A. RETTY; Geological Exploration along the Laflamme River, Abitibi Co., by CARL FAESSLER; Pusticamica Lake Map-Area, Abitibi District, by G. S. MACKENZIE.

Deserts on the March. P. B. SEARS. Pp. 231. Univ. of Oklahoma Press, Norman, Okla., 1935. Price $2.50. An interesting non-technical story of deserts and semi-arid regions contrasted with humid regions; of the life that lives there; desert control of soil, agriculture, settlement, living conditions, and industry; much of western history although little of deserts. Quite entertaining.

The East African Plateaus and Rift Valleys. BAILEY WILLIS. Pp. 358, pls. 72 (including maps), figs. 16. Studies in Comparative Seismology, Carnegie Institution, Publ. 470. Washington, 1936. An extensive description of African rift valleys and plateaus, and author's hypothesis of origin; earthquakes, gravity tests, and vulcanism are briefly mentioned.

SCIENTIFIC NOTES AND NEWS

H. Foster Bain has returned to New York from the Far East and has been associated for the summer in professional work with Samuel H. Dolbear and Lawrence B. Wright.

J. E. Spurr has been spending the summer as usual at his farm at Alstead, N. H. The rest of the year he is at Winter Park, Fla., where he gives a course in geology at Rollins College.

Edward Sampson, head of the department of geology at Princeton, has been directing a search for molybdenite in Newfoundland this summer.

M. E. Hurst is carrying out further detailed study of the Porcupine area, Ont., with a view to the revision of the geological information of that section.

E. L. Bruce is continuing geological work in an area between Little Long Lac and Jellicoe, Ont.

J. K. Gustafson, since 1934 geologist for Western Mining Corp., and Gold Mines of Kalgoorlie in Western Australia, has been engaged by Zinc Corp., Ltd., North Broken Hill Ltd., and Broken Hill South Ltd. to make a detailed study of the Broken Hill lodes. Dr. Gustafson was with the Hollinger Mine in Canada prior to going to Australia.

Edwin T. Hodge has been appointed Director of a mineral survey for Bonneville Dam, to furnish to prospective purchasers of surplus Bonneville power information on the economically available mineral deposits of the Northwest.

Anton Gray has returned to London from Rhodesia and Egypt.

J. B. Stone, for three years chief geologist for Bendigo Mines, Ltd., will return to the U. S. in September, stopping over at Fiji on the way.

M. W. Hayward, consulting engineer and geologist at El Paso for the American Metal Co., John G. Barry, consulting mining geologist, also of El Paso, and John W. Vanderwilt, of Denver, geologist for the Climax Molybdenum Co.; all have recently been at Fairplay, Colo., representing the Park Range company in connection with an apex suit that the Park Range Mining and Prospecting Co. has brought against the London Gold Mining Co.

J. E. Thomson has commenced a detailed study of the Pickle-Crow area, Ont.

R. C. Wallace has been appointed Principal and Vice Chancellor of Queen's University.

F. S. Turneaure, chief of the exploration department of Patiño Mines & Enterprises, has returned to Bolivia for his third contract after having spent three months on leave in the States.

Dorsey Hager is a member of the firm of Hager & Howard that has recently opened an office at 601 Union Trust Bldg., Winnipeg, Man.

Gerald G. Dobbs, general manager of Ariston Gold Mines, Ltd., Prestea Gold Coast, West Africa, who has been on leave in England, has returned to the Gold Coast.

C. W. Vaupell, geologist, and Jose A. Garcia, mining engineer, announce the opening of offices at 411–412–413 Ave. Juarez No. 30, Mexicc City, D. F.

The Department of Geology and Geography of Northwestern University was addressed during the past academic year by the following lecturers: G. H. Anderson (Cal. Inst. of Tech.), "Migmatites of the Inyo Range"; G. H. Cady (Ill. Geol. Surv.), "The Classification of Coal"; J. L. Gillson (duPont), "The Monazite Deposits of Travancore"; W. H. Howard (Univ. of Ill.), "Petroleum in Limestone Reservoirs"; M. S. Krishnan (Geol. Surv., India), "The Geology of India"; J. E. Lamar (Ill. Geol. Surv.), "The Physiography of the Front Range"; L. L. McCabe (Ill. Geol. Surv.), "Phases of Coal Research." Also W. H. Bucher of the Univ. of Cincinnati gave five lectures on "Problems of Geotectonics."

The Pennsylvania Geological Survey celebrated its centennial June 12, 13, with addresses, a symposium on "The Mineral Industry and the Geological Survey," and three field trips near Harrisburg.

Fred E. Melzer, mining engineer and geologist, who had practiced his profession in Mexico, New Mexico, and Colorado, died on June 15, 1936, at the age of 39.

D. G. H. Wright, of Toronto, has been elected vice-president and consulting engineer for Minefinders, Ltd.

J. B. Mawdsley, Canadian geologist, has been appointed managing director of Ceres Explorations, Ltd.

L. B. Riley has been appointed to the geological staff of the Anaconda Copper Mining Co., with headquarters at Salt Lake City.

S. R. Brockunier was burned to death in a forest fire in the Little Rockies while engaged in geological work for the U. S. Geological Survey.

D. F. Hewett, chief of the Section of Metalliferous Deposits of the U. S. Geological Survey, has returned from a trip of inspection of the work of field parties in the western states.